



Infrared detectors

Military uses have given way to a wide range of general applications with the development, since the 1940's, of polycrystalline-film and, later, single-crystal infrared photon detectors.

Henry Levinstein

Infrared radiation has been studied with detectors of one kind or another since about 1800. The difference between the techniques of the first century-and-a-half and the period since World War II is that the earlier devices were thermal detectors, responding to temperature change caused by integrated absorption of energy, while the more recent devices are true *photon* detectors. In the latter type, interaction of individual photons (above a certain threshold energy) with the solid detector results directly in electron emission or charge-carrier excitation.

Here we shall be concerned mainly with the developments since World War II—from the polycrystalline films of the 1940's, to the single-crystal extrinsic and intrinsic materials that transistor technology made possible and, most recently, to new materials that can be tailored to fit particular needs by appropriate manufacture. Parameters of all these detectors that set limits to their performance are their speed of response, spectral response and "detectivity"—the reciprocal of the minimum detectable power.

While the detector is the principal component of any system, their proper function requires optical devices that may be placed between source and detector, and display devices that follow the detector and its associated electronics. "Optics" may involve dispersive elements (gratings or prisms) if wavelength dependence is sought, or focussing if total radiation is to be measured. The form of the display device will depend strongly on the application in question; figure 1 shows

some examples and others are illustrated later. If the operating medium is the atmosphere, we will need to remember the "windows" (at 1–2.5, 3–5 and 8–14 microns) in which appreciable transmission is possible. The thermal background that emits radiation in the same wavelength range as the infrared source will compete at the detector with radiation from the source and will have a deteriorating effect on the detecting capability of the system.

Applications, stemming largely from military requirements at one time, are now to be found in many different arenas, and this article closes with a brief selection.

Thermal and photon detectors

In thermal detectors the incident energy must be absorbed, thereby producing a temperature change in the absorbing layer (usually a blackened surface). This temperature change can be made to produce any of a variety of effects, such as a voltage when a junction between unlike metals is heated (thermocouple), a change in resistance of a metal or semiconductor (bolometer), change in polarization of certain dielectric materials (pyroelectric detector) or change in pressure of an enclosed gas (Golay cell). Such thermal detectors can be made to respond uniformly over a wide spectral region when they employ layers whose absorption is wavelength invariant. Because the detecting process of these detectors requires that the sensing element warms and cools, they do not respond well to rapidly changing radiation.

In photon detectors, on the other hand, the incident photon flux interacts with

the solid, causing electrons to be emitted if the photons have sufficient energy, or causing charge carriers to be excited between valence and conduction bands of semiconductors (intrinsic detectors) or between impurity states and one of the bands (extrinsic detectors). This excitation results in a change of charge carrier density of the semiconductor and therefore a change of its conductivity. A certain minimum energy is required to produce either emission or excitation; therefore photon detectors have a long-wavelength threshold, λ , beyond which they do not respond. This threshold wavelength is given by $\lambda = hc/E$, where h is Planck's constant, c the velocity of light and E the work function of the emitting surface or the activation energy of the semiconductor. It may be written

$$\lambda(\text{microns}) = \frac{1.24}{E(\text{eV})}$$

The major effort in the past thirty years has been to extend the long-wavelength threshold so that the detector would respond in the 3–5 and 8–14-micron atmospheric windows and thereby detect objects at ambient temperature (with a radiation peak occurring at about 10 microns).

Despite considerable effort to lower the work function of photoemissive surfaces, there appears to be no available emitter with a response beyond 1.2 microns. The most significant advances in photon detectors have come in the area of photoconductive detectors.

Detector parameters. Most infrared photon detectors are operated either in the photoconductive or in the photovoltaic mode. When operated in the photo-

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Infrared imagery. The top photograph shows an electrical power station as seen at 11 pm from a plane at 500 feet, using a HgCdTe detector array. Black is cold, white is hot; note that one transformer in the transformer bank is very white, indicating that it is much hotter than the others. The lower photograph is an isometric microimage of a gate circuit, generated by a liquid-nitrogen-cooled InSb detector. Photographs supplied by Texas Instruments Inc, Dallas, Texas (top) and Barnes Engineering Co, Stamford, Conn. (bottom).

Figure 1

toconductive mode they are connected to a dc voltage source and a load resistance. An incident photon of sufficient energy frees a charge carrier in the solid, resulting in an increased conductivity. Under equilibrium conditions with constant photon flux falling onto the detector, the number of charge carriers recombining either at recombination centers or with carriers of the opposite sign and thereby becoming immobilized is equal to the number generated. When the photon flux is removed, conductivity decays to its starting value. In the photovoltaic mode a p-n junction supplies a builtin electric field and no external battery is required. Either the p or the n region of the junction is made very thin, so that radiation passing through the thin layer reaches the junction where the carriers are excited. The parameters describing an infrared detector are related directly to the physical properties just described.

The **speed of response** of a detector is determined by the length of time a charge carrier remains mobile after excitation. It depends on the number of recombination centers and their capture cross section, and it may be measured by shining

square radiation pulses onto the detector and observing the decay. If this decay is exponential, the time constant is well defined by the time for the signal to decay to $1/e$ of its equilibrium illuminated condition. Because the decay is usually not exponential but much more complicated, time constants are frequently defined as the time taken for the signal to drop from 90% to 10% of its illuminated value. Time constants range from a few hundred microseconds for older detectors to less than 1 nanosecond for some of the modern detectors. The value for a particular detector may depend on the temperature of the detector, the amount of background radiation striking it and for some detectors the wavelength of the incident radiation. The amount of variation depends on the complexity of the recombination process.

Spectral response. If one assumes constant quantum efficiency and uses a constant incident photon flux, the detector response should remain wavelength invariant until it drops to zero when photons have insufficient energy to excite charge carriers. Spectral measurements are usually made for constant energy

rather than constant photon flux; so they should show a linear increase in response to the spectral peak. In practical detectors the response may deviate somewhat from linearity, and the cutoff is not necessarily sharp.

The **detectivity** is the quantity most frequently used to describe the minimum power that a detector can "see." It is given by the relation

$$D = \frac{(S/N)}{P}$$

where S is the signal voltage measured at the detector when incoming radiation is sinusoidally modulated by a rotating sectored disk, N is the noise when the signal is blocked off and P is the power at the detector, usually from a 500 K black body. As the noise depends on amplifier bandwidth (Δf) and on the detector area (A) the detectivity is usually normalized to detectors with 1 cm^2 area and amplifiers of 1 Hz bandwidth. This yields¹ the normalized detectivity D^*

$$D^* = \frac{(S/N)}{P} (A \Delta f)^{1/2}$$

The assumption made in the normalization process requires that detector noise varies as $A^{1/2}$ and $(\Delta f)^{1/2}$, an assumption that is not always entirely correct. When the spectral response and D^* are known, D_{λ}^* , the detectivity at a particular wavelength, may be evaluated. This detectivity D_{λ}^* is a particularly useful concept, because its theoretical limit may be calculated. After a reasonable period of development, some of the best detectors may approach this limit to within 10%, and the average detector to within 50%. The calculation requires first an analysis of detector noise. Johnson noise—due to the random motion of charge carriers—is present in all conducting solids, but it is negligible in comparison with other forms of noise in semiconductors. $1/f$ noise, the type of noise whose power varies inversely with frequency, appears to have a variety of causes including surface effects.² Proper production techniques usually make it negligible above 100 Hz and often above 20 Hz. We are left with noise produced by fluctuations in the generation and recombination of charge carriers. This effect may be due to thermal generation of charge carriers by lattice vibrations or by fluctuations in photons arriving from the background.³ The detector should be cooled sufficiently, for a particular activation energy, that thermal generation is negligible. It is then said to be "background limited" (BLIP operation), and the normalized detectivity is⁴

$$D_{\lambda}^* = \frac{1}{2hc} \left(\frac{\eta}{Q_B} \right)^{1/2}$$

where η is the quantum efficiency and Q_B the photon flux from the background. Q_B can be evaluated from a knowledge of the background temperature and the de-

detector's angular field of view. For the ideal detector η is taken as unity. With these assumptions, the background-limited detectivity D_{λ}^* may be calculated, with results as shown in figure 2.

For photovoltaic detectors D_{λ}^* is greater by $\sqrt{2}$ than for the equivalent photoconductive detector, because one need consider only noise produced by the generation of charge carriers but not by their recombination.

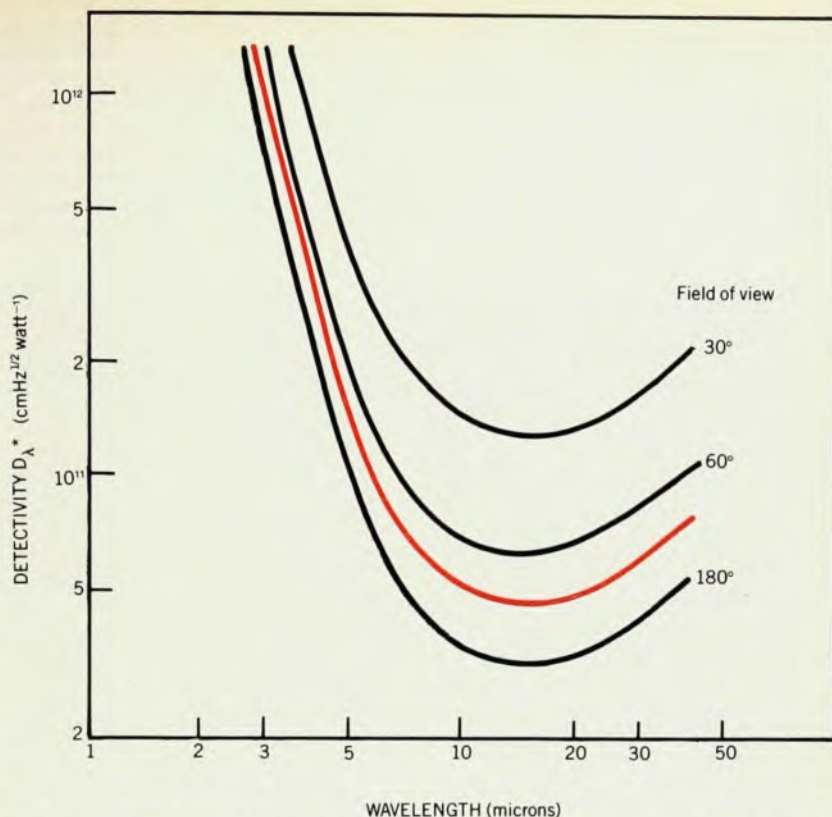
Notice that D_{λ}^* can apparently be increased to virtually any value by reducing the background radiation; one could use cold apertures to reduce the detector's field of view, or one could use filters to reduce the spectral range that the detector "sees." A reduction in background radiation, however, usually requires additional detector cooling for the number of thermally excited charge carriers to remain negligible. Furthermore such a reduction in background will lengthen the time constant and, if filtering is improperly done, it may reduce radiation from the source.

Early film detectors

Photon detectors produced between about 1940 and 1950 had one thing in common; they consisted of polycrystalline films prepared by a variety of techniques⁵ that were not well understood then and are not well understood now. Their performance could be duplicated only by carefully following recipes, which were developed and improved by trial and error. It is interesting to note that some of these detectors are used even today, and are still prepared by the same empirical methods as before. Improved controls have made their characteristics more reproducible, however. The materials developed were Ti_2S_6 and the chalcogenites PbS ,^{6,7} PbSe ⁶ and PbTe .⁸ Of these materials, PbS and PbSe have survived. PbTe , though it could be produced in the laboratory, did not lend itself to the early production techniques. PbS detectors were originally produced by evaporating PbS and condensing it onto a substrate, then "sensitizing" the resulting film by heating it in oxygen. More uniform and reproducible PbS detectors were later prepared by chemical deposition from solution, followed by empirical sensitization methods. They respond to wavelengths as long as about 3 microns. Their characteristics are shown in figure 3 and in the table on this page.

Because these detectors can be prepared in large batches and require no cooling (with the associated Dewar construction) single elements are cheap, and they find frequent applications when their characteristics meet the given requirements. On cooling their response can be extended somewhat to longer wavelengths; but the increased time constant may make other detectors more desirable.

As one proceeds to materials with a



Background-limited detectivity at spectral peak as a function of long-wavelength threshold. The three black curves represent photoconductive detectors with three different fields of view; the colored curve is for a photovoltaic detector with a 180° field of view. Figure 2

smaller energy gap (longer-wavelength response) cooling becomes necessary and the longer the wavelength the more cooling is usually required. PbSe , which like PbS was first prepared by evaporation and then by chemical deposition from solution, responds to about 7 microns when cooled to liquid-nitrogen temperature (80 K), 5 microns when cooled to dry-ice temperature (200 K). Detectors to be used at 200 K must be prepared especially for that operating temperature. This temperature (200 K) is conveniently reached with thermoelectric coolers, and because the region between 5 and 7 mi-

croons which is accessible only to liquid-nitrogen-cooled detectors is not in an atmospheric window, detectors of the 200-K type are preferred over the liquid-nitrogen detector and are still used frequently today. Their characteristics are shown in figure 3 and in the table below.

The solid-state era

The development of the transistor and the accompanying crystal-growing and material-purification techniques ushered in a new era for infrared detectors. Two separate paths have been followed for producing detectors from single crystals;

Characteristics of typical detectors

Material	Operating temperature (K)	Peak wavelength (microns)	Peak detectivity D^* ($\text{cm Hz}^{1/2} \text{ watt}^{-1}$)	Time constant (microsec)
PbS	300	2.5	10^{11}	300
PbSe	200	4.8	2×10^{10}	20
InSb (PV)	80	5.0	10^{11}	0.2
Ge: Au	80	5.0	10^{10}	0.001-0.1
Ge: Hg	30	10	10^{10}	0.0002-0.1
Ge: Cu	4	20	2×10^{10}	0.01-0.1
PbSnTe (PV)	80	11	$1-2 \times 10^{10}$	~ 1
			1×10^8	~ 0.01
HgCdTe (PC)	80	11	$1-2 \times 10^{10}$	~ 0.5

Field of view is 180° in each case

they lead to extrinsic and intrinsic materials respectively.

While germanium and silicon have a response to 1.7 and 1.1 microns respectively, due to transitions between valence and conduction bands, response to longer wavelengths was obtained by intentionally adding impurities and then producing transitions between the impurities and

one of the bands.¹⁰ Virtually every impurity in germanium was tried.¹¹ Early detectors that are still in use include Ge:Au^{12,13} with a response to about 10 microns and a peak at about 5 microns, Ge:Cu¹² with a response to about 30 microns, Ge:Zn¹⁴ with a response to about 40 microns, and Ge:B¹⁵ with a response to about 100 microns. Figure 4 compares

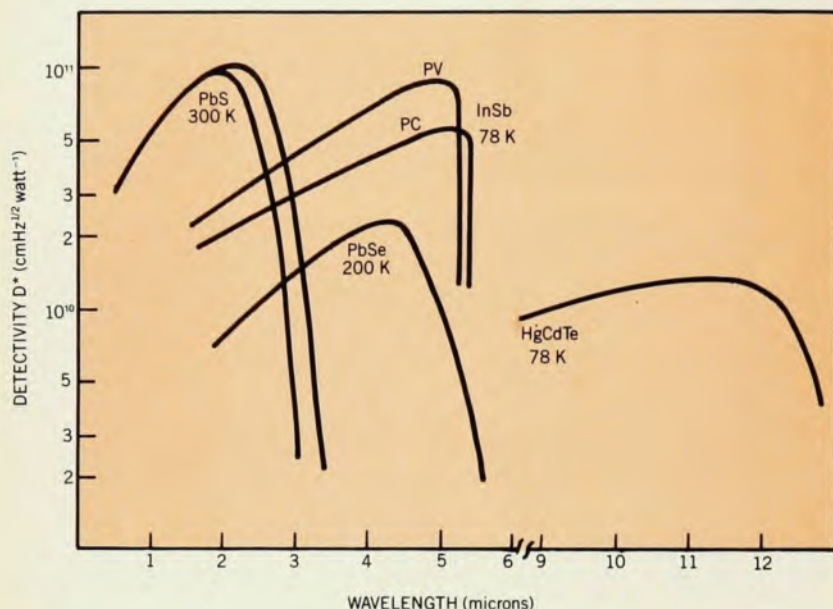
these detectors, and the table gives a summary of their characteristics. Detectors with longer wavelength response had, of course, more stringent cooling requirements. Perhaps the most widely used detector of this group was Ge:Hg.¹⁵ With a response to about 12 microns it was the first detector of significant value in the 8–14-micron atmospheric window that did not have to be cooled with liquid helium. Its coolant temperature of about 30 K could be obtained with mechanical coolers, which were developed at about the same time. The time constant of these detectors could be adjusted simply by adding or removing recombination centers (other impurity atoms) during crystal growth.

At the same time as the research on extrinsic materials there was considerable effort to replace intrinsic film detectors with single-crystal detectors, which have better understood and more reproducible parameters. Most success was achieved with compounds of elements in columns III and V of the periodic table. InSb¹⁷ was developed with a response to about 5.5 microns. It could be prepared to function in the photoconductive mode (PC) and (when a p–n junction was formed near the surface) in the photovoltaic mode (PV).¹⁸ Most InSb detectors in use today function in the PV mode. Although InSb detectors were superior to PbSe when cooled to 80 K they are inferior to PbSe when both are used at dry ice temperatures (200 K). This changeover is due, in part, to the fact that as the temperature is raised above 80 K the threshold for InSb shifts to longer wavelengths where the response is not needed, whereas for PbSe it shifts to shorter wavelengths. The table on page 25 and figure 3 show the characteristics of InSb detectors.

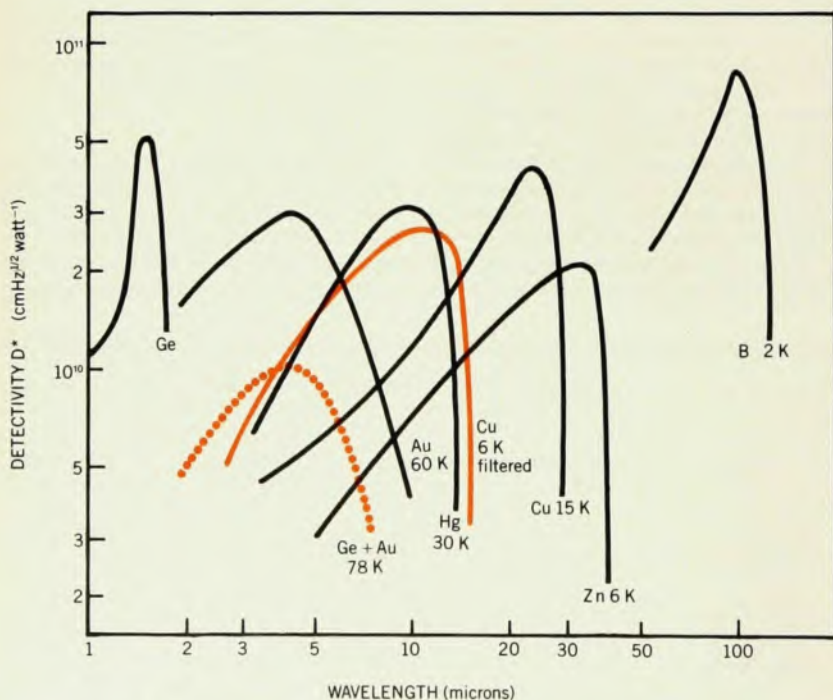
Detectors of InAs were developed to compete with PbS. However, at room temperature they were always inferior to PbS and while good cooled detectors could be produced, they have never found wide applications.

Detectors with adjustable energy gap

The past ten years have seen the development of two new materials, HgCdTe and PbSnTe. Both possess the inherent advantage that, by controlling the composition of the material, the long-wavelength threshold of the detector may be designed to fit particular needs. Initially, work was performed only on HgCdTe.^{19,20,21} Adjusting the fraction of HgTe and CdTe in the final crystal allowed photoconductive detectors with response to about 12 microns to be constructed. These detectors could be operated at liquid-nitrogen temperature and somewhat higher, and thus require simpler mechanical coolers than impurity-activated germanium detectors. They are especially suitable for space use, where radiation cooling will yield the required



Spectral response of typical intrinsic detectors, for an angular field of view of 180° and temperatures of operation as shown. See also the table on page 25. Figure 3



Impurity-activated germanium detectors. The curves compare spectral response for the materials and temperatures shown. The curve labelled "B" is for a 10° field of view; all seven others are for a uniform 60° field of view. Figure 4

temperature. Because of production and storage problems, which in the early stages of development seemed serious, work on PbSnTe was begun²² with the expectation that it would be easier to prepare and more stable in use.

This material, PbSnTe, must be operated in the photovoltaic mode and, when the proper fraction of PbTe and SnTe are used in the single crystal, characteristics at 12 microns are similar to HgCdTe. Because of the higher dielectric constant, time constants of PbSnTe are usually longer than for HgCdTe. Because most of the production problems for HgCdTe appear now to have been solved, PbSnTe has been relegated to a backup material. Constructing HgCdTe in the PV mode yields response times in the sub-nano-second range; there is currently an effort to produce HgCdTe detectors with a variety of long-wavelength thresholds both in the PV and PC modes. The method of preparation of the single-crystal material must be varied to achieve the desired long-wavelength threshold. There is considerable hope that the 5-micron HgCdTe detectors operated at dry-ice temperatures will eventually replace PbSe. Whether an uncooled 3-micron HgCdTe detector will ever replace PbS has not yet been determined. The HgCdTe detectors with a response considerably beyond 12 microns have also been constructed, but their applications are more limited.

Detector arrays

As will be pointed out later many applications require arrays of detectors rather than single elements. Cooled detectors must be operated in a vacuum Dewar, with the requirement that a two-hundred-element array, say, needs more than 200 leads to be taken through the Dewar. As the number of elements increases this task becomes impossible. The use of detector arrays in conjunction with charge-coupled devices, mounted in the same vacuum Dewar, would require many fewer leads and would thus simplify the entire processing technique. Several approaches are currently being considered: combinations of detector material with silicon charge-coupled devices; the use of impurity-activated silicon detectors with silicon charge-coupled devices, and the use of intrinsic detector materials and charge-coupled devices prepared from the same material.

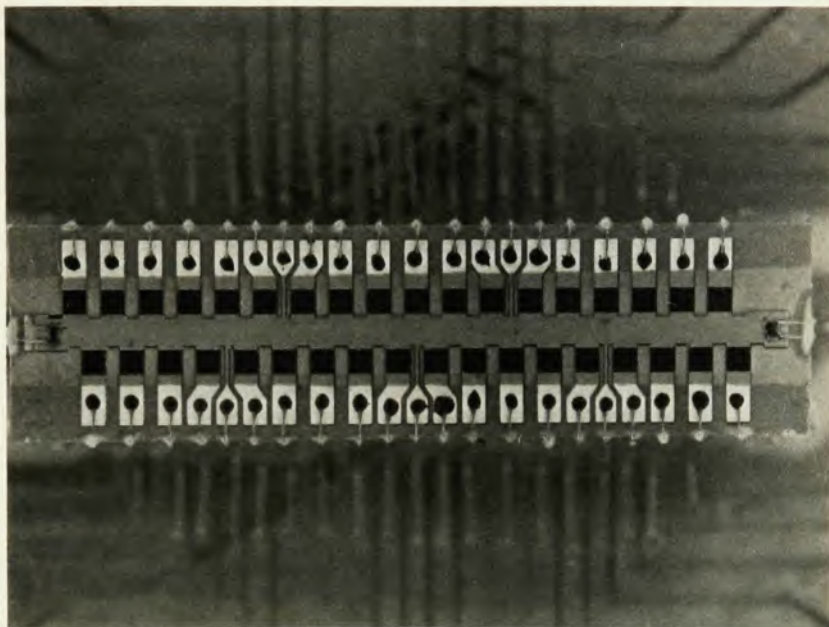
This work has renewed the interest in extrinsic silicon detectors.²³ The activation energies of impurities in silicon have been known for many years, and photoconductive properties were reported²⁴ as early as 1967. A serious disadvantage of these detectors is that, so far, no impurities have been found to cover exactly the 8-14-micron atmospheric window and was the case for germanium with mercury impurities. Thus impurities with lower activation energy have to

be used, requiring cooling to lower temperature. In the 3-5-micron range, impurity-activated silicon will require lower cooling temperatures than HgCdTe. However, silicon technology for producing sophisticated arrays in conjunction with charge-coupled devices is so much farther advanced than for any other material that one may be willing to accept the more

stringent cooling requirement—at least for the immediate future.

Applications

The rapid development of infrared detectors during the past 30 years was undoubtedly due to military interest and support. It was realized that systems containing infrared photon detectors



Multielement array. In this 32-element HgCdTe detector array, each element is 0.25 mm square. Photograph supplied by Honeywell Radiation Center, Lexington, Mass.

Figure 5



A ship in Boston Harbor taken in darkness from the Prudential Building, using a HgCdTe detector array. The white object in the foreground is a warm smokestack. Photograph supplied by Honeywell Radiation Center, Lexington, Mass.

Figure 6

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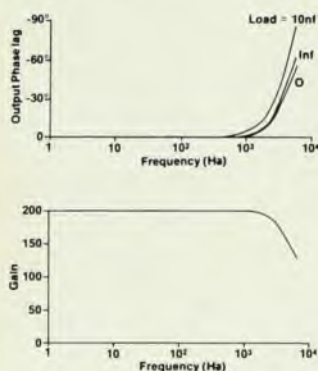


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could be used in secure communications where a voice-modulated infrared source could be focussed onto a detector, in heat homing where a missile containing a detector could be guided to a hot object, and in reconnaissance where warm objects could be differentiated from a cooler background. In recent years, many of the military developments have been modified for scientific and industrial use. While applications²⁵ are far too numerous to detail, let us look at a few examples.

An active reconnaissance system developed during World War II included an infrared source that consisted of an incandescent light bulb with a filter to eliminate visible radiation but retain near infrared. When this source was directed at a night scene, reflected radiation, focussed onto a low work-function layer, caused electrons to be emitted and focussed onto a fluorescent screen where they could be observed. Military uses of the device are limited, because the enemy, who may also use a similar detecting device, will know he is being observed. The devices are now used in the study of near-infrared sources, by hunters and police departments. Systems employing PbS detectors, developed in Germany toward the end of World War II, could scan the night sky and detect hot airplane engines at considerable distances. Objects at ambient temperatures could not be located, because they emit an insufficient number of photons in the 1-3-micron spectral region where PbS responds. The development of detectors with response to 5 microns (and, later, 13 microns) led to a variety of scanning systems. Radiation from the object to be studied is focussed onto the detector, often by rapidly moving mirrors that see a small area of the object and scan across the object, line by line. The detector output may be recorded on magnetic tape and later displayed on a TV screen; it may be fed to light-emitting diodes for observation or photographic recording, or it may be fed directly through appropriate electronics to a TV monitor and observed or photographed. In any case, a thermal image that distinguishes objects at different temperatures is obtained. For some applications different temperatures appear as different shades of grey, for others, after electronic processing, as different colors on a TV screen. It is often necessary to scan rapidly to obtain a high frame rate and more lines per frame; so one detector is no longer sufficient and arrays with an ever increasing number of elements are being used (see figure 5). Infrared systems are now employed to locate surface tumors (which are slightly warmer than the rest of the body), to study blood circulation of the body, to detect sources of pollution in rivers and lakes, to study heat flow from poorly insulated homes, to look for flaws in electronic circuitry, to examine Earth resources from planes or satellites, to check

for invisible cracks in coal mines, to study thermal gradients in the atmosphere, and to determine the location of forest fires.

Figures 1 and 6 show examples of infrared imagery taken with a variety of systems designed for specific needs. There appears now to be little doubt that infrared photon detectors have been developed to the point where their use for particular application is limited to a large extent by the ingenuity of the system designer and the financial resources available. Further detector research is still needed, however, because a better understanding will make it possible to anticipate their behavior in particular applications.

References

1. R. C. Jones, *Proc. IRE* **47**, 1495 (1959).
2. A. U. MacRae, H. Levinstein, *Phys. Rev.* **119**, 62 (1960).
3. K. M. van Vliet, *Proc. IRE* **46**, 1004 (1958).
4. P. Bratt, W. Engeler, H. Levinstein, A. U. MacRae, J. Pehek, *Infrared Phys.* **1**, 27 (1961).
5. T. S. Moss, *Proc. IRE* **43**, 1869 (1955).
6. R. J. Cashman, *Proc. IRE* **43**, 1471 (1955).
7. J. N. Humphrey, *Appl. Opt.* **4**, 665 (1965).
8. D. E. Bode, H. Levinstein, *Phys. Rev.* **96**, 259 (1954).
9. D. E. Bode, T. H. Johnson, B. N. McLean, *Appl. Opt.* **4**, 327 (1965).
10. H. Levinstein, *Appl. Opt.* **4**, 689 (1965).
11. R. Newman, W. W. Tyler, *Sol. State Phys.* **8**, 49 (1959).
12. M. L. Schultz, G. A. Morton, *Proc. IRE* **43**, 1819 (1955).
13. L. Johnson, H. Levinstein, *Phys. Rev.* **117**, 1191 (1960).
14. E. Burstein, J. F. Jacobs, G. S. Picus, in *Proc. Int. Comm. Opt.*, Stockholm (1957).
15. H. Shenker, W. J. Moore, E. H. Swiggard, *J. Appl. Phys.* **35**, 3965 (1964).
16. S. Borrello, H. Levinstein, *J. Appl. Phys.* **33**, 2947 (1962).
17. F. F. Rieke, L. H. DeVaux, A. J. Tuzzulini, *Proc. IRE* **47**, 1475 (1959).
18. G. R. Pruett, R. L. Petritz, *Proc. IRE* **47**, 1524 (1959).
19. W. D. Lawson, S. N. Nielson, E. H. Putley, A. S. Young, *J. Phys. Chem. Sol.* **9**, 325 (1959).
20. P. L. Kruse, *Appl. Opt.* **4**, 687 (1965).
21. D. Long, T. L. Schmit, in *Semiconductors and Semimetals, Volume 5*, R. Willardson, A. Beers, eds., Academic, New York (1970).
22. I. Melngailis, T. Harmon, in *Semiconductors and Semimetals, Volume 5*, R. Willardson, A. Beers, eds., Academic, New York (1970).
23. N. Sclar, *Infrared Physics* **16**, 435 (1976).
24. R. A. Soref, *J. App. Phys.* **38**, 5210 (1967).
25. A series of papers on applications may be found in the special issue on "IR Technology for Remote Sensing," *Proc. IEEE*, January 1975.