Photoconductive Cells for Detection of Infrared Radiation

O. Simpson and G. B. B. M. Sutherland

Department of Physics, University of Michigan, Ann Arbor

WITHIN THE PAST FIVE YEARS photoconductive cells have become available for the detection of infrared radiation in the range between 1.5 μ and about 5.5 μ. These were developed or partially developed for military purposes in the years 1939–45 but are now finding many valuable and interesting applications of a purely scientific and industrial nature. It is the purpose of this article to review briefly some of their applications and published information concerning the performance of such detectors so that those unfamiliar with them may be able to estimate their capabilities for other applications. We shall not consider detectors that have a long wave limit of detection below 1.5 μ, since there are a great many photodetectors of this type, the most generally useful photoconductor in this range being the thallium sulfide ("Thalofide") cell with a limit at about 1.2 μ.

Among the materials that are photoconductive beyond 1.5 μ there are three that have been intensively studied and shown to have useful properties as infrared detectors; these are lead sulfide, lead selenide, and lead telluride. It is necessary to have such a material in the form of a thin layer (10^{-4} to 10^{-5} cm) deposited either by evaporation or by chemical means on a nonconductor (generally glass); in most cases, some oxygen is deliberately introduced into the layer. The dark resistance of such a layer may be between 10^4 and 10^8 ohms, and the response time between 10^{-5} and 10^{-3} seconds.

In Table 1 we have attempted to summarize the essential features of these three types of cell which can be prepared in several ways and operated under various conditions. Methods of preparation have been described for (*a*) lead sulfide by Sosnowski, Starkiewicz, and Simpson (*1*), Kicinski (*2*), and Cashman (*3*); (*b*) lead selenide by Blackwell, Simpson, and Sutherland (*4*) and Milner and Watts (*5*); (*c*) lead telluride by Simpson and Sutherland (*6*). Lead sulfide layers can be made which are excellent photoconductors at room temperature, even when exposed to the atmosphere. The better layers usually have to be kept *in vacuo,* and a considerable improvement is usually obtained in the responsivity by cooling the layer to the temperature of solid CO_2. Further cooling to the temperature of liquid air and liquid hydrogen enhances this effect somewhat and also causes the long wave limit of sensitivity to move from 3.3 μ to about 3.6 μ (*7*). However, since the resistance of the layer increases very rapidly as the temperature is lowered, and the time of response is markedly increased, it is not always advantageous to work with a cooled cell. On the other hand, selenide and telluride cells do not show a usable photoconductivity unless cooled to at

TABLE 1

	Lead sulfide	Lead selenide	Lead telluride
Special range	Visible to 3.0 μ	Visible to 4.5 μ	Visible to 5.5 μ
Method of preparation	Evaporation or chemical precipitation	Evaporation or chemical precipitation	Evaporation
Operating conditions	1) Room temperature open to atmosphere 2) Room temperature *in vacuo*		
	3) Low temperature (−78° C to −190° C) *in vacuo*	Low temperature (−190° C) *in vacuo*	Low temperature (−190° C) *in vacuo*
Availability	British Thompson Houston Company, Rugby, Eng. (*1–3*)		
	Photomho Chicago, Ill. (*2*)	Not commercially available	Not commercially available
	Continental Electric Chicago, Ill. (*2*)		
	Eastman Kodak Rochester, N. Y. (*1–3*)		
Response time	1) 4×10^{-5} sec at 20° C 2) $4–10 \times 10^{-5}$ sec at 20° C 3) $2–7 \times 10^{-4}$ sec at −190° C	$3–10 \times 10^{-5}$ sec at −190° C	$1–5 \times 10^{-4}$ sec at −190° C

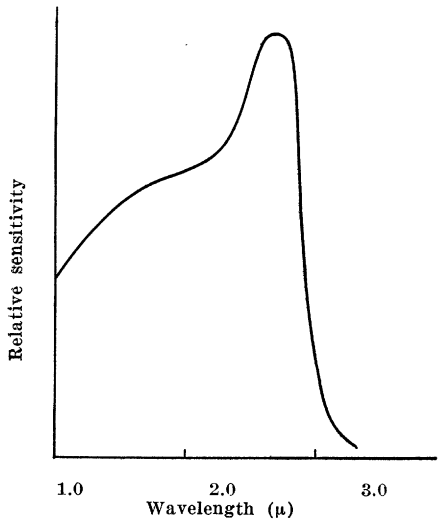

FIG. 1. The spectral sensitivity of a lead sulfide cell.

least −78° C, and in practice they must be operated at liquid nitrogen temperatures.

At present only lead sulfide cells are commercially available. All three types have a nonuniform response with respect to the various wavelengths to which they are sensitive. A typical curve of responsivity as a function of wavelength is shown for lead sulfide in Fig. 1. In lead selenide the maximum is between 3 μ and 4 μ, and for lead telluride it is a little beyond 4 μ. However, the responsivity curves are very sensitive to the method of preparation, and the positions and widths of the maxima vary considerably. The lead sulfide cells that are operable at room temperature are generally peaked closer to 2 μ than 3 μ.

Additional information about the characteristics of these cells (e.g., frequency response and dependence of noise on frequency) can be found in review articles by Elliott (*8*), Sutherland and Lee (*9*), and Smith (*10*). In this article we shall discuss principally the performance of these cells as radiation detectors and in particular review the question of how closely they approach the theoretical limit of being "perfect" detectors.

Whenever a radiation detector has to be chosen for a particular purpose, it is necessary to compare the performance of all available types before selecting the one that is likely to give the best results under the proposed experimental conditions. There is, however, no simple "figure of merit" for the comparison of detectors that will be valid for all possible applications. For example, the detector in a spectrometer designed for high resolution work must have primarily a very low noise equivalent power, whereas the detector in a spectrometer designed for oscillograph presentation of spectra must have, primarily, a very short time of response. In order to estimate the performance of a photoconductive detector under arbitrary operating conditions, it is therefore necessary to specify two quantities—(*a*) the responsivity, defined as the output in microvolts per microwatt incident power, as a function of frequency, exciting current in the detector, temperature of the detector, and wavelength of the incident radiation; (*b*) the noise power per unit band width as a function of the same variables. Unfortunately such extensive data are rarely available, and it is the common practice to define a single parameter, or figure of merit, for the purpose of comparison under some specified operating conditions. Daly and Sutherland (*11*) have considered a figure of merit for a detector used in the cathode-ray presentation of infrared spectra. They chose as a criterion the energy in a pulse signal that will be just detectable above noise, the over-all band width of the amplifier-display system being adjusted to a value appropriate to the optimum radiation pulse length. They show that the minimum pulse energy is proportional to $(\mu\tau^{1/2}/\sigma)$, where τ is the time constant of the detector (assumed to have a simple exponential response), μ is the mean square noise voltage per unit band width originating in the detector, and σ is the zero-frequency responsivity. From the data then available they concluded that under this criterion, and working at the optimum wavelength, lead sulfide and lead telluride detectors are between 10 and 100 times better than superconducting bolometers, and these in turn are about 100 times better than Schwartz-type thermocouples.

Apart from the question of the actual sensitivities of existing detectors, the theoretical ultimate sensitivity of a particular type of detector is of interest in showing how far below the ideal any given detector may be. The limiting sensitivity is determined by the responsivity to radiation and by the noise in the detector. The mean square noise, or noise power, is the sum of contributions from all sources, including Johnson noise and noise due to fluctuations in both the exciting current and in the incident radiation flux (*12, 13*). In the normal method of operation of a detector, the exchange of radiation between the sensitive element and its surroundings greatly exceeds the incident signal radiation. When all other sources of noise are negligible, fluctuations in the background radiation will impose a theoretical limit on the smallness of a detectable signal, beyond which no improvement is possible. Jones (*14*) has discussed this source of noise as the cause of the ultimate limit of sensitivity in a number of different detectors, and Fellgett (*15*) has extended Jones' method to apply to photoconductive lead sulfide and lead telluride detectors. Fellgett calculated the limiting sensitivity, imposed by radiation fluctuation, for a lead sulfide and a lead telluride cell from their measured responsivity-wavelength characteristics. The assumption was made that the cells were cooled, but exposed to a solid angle 2π of radiation from surroundings at 15° C. Under these conditions the ultimate sensitivity of the lead sulfide detector was calculated as 2.1×10^{-13} watt at the optimum wavelength, compared with the measured noise equivalent power 4.9×10^{-13} watt. Both figures referred to unit band width. The corresponding figures for the lead telluride detector were 2.3×10^{-13} and

4.4×10^{-13} watt. These results show that the total noise in the detectors was only about twice as great as that due to radiation fluctuations alone. Simpson (*16*) has shown that the conductivity of a lead telluride photoconductor at $-190°$ C is increased 10 to 100 times by exposure to background radiation from surroundings at room temperature. Under the conditions prescribed by Fellgett, therefore, almost the entire current in the detector appears to be photocurrent. It is thus not surprising that the noise should arise primarily from fluctuations in the incident flux.

Moss (*17*) has discussed the same question, and in particular has investigated the dependence of the ultimate sensitivity, for various signal wavelengths, on the shape of the spectral responsivity curve. Since in the case of photoconductive detectors the majority of the background radiation is normally of greater wavelength than the wavelength for maximal responsivity, it is disadvantageous for a detector to have appreciable photosensitivity at wavelengths greater than that of the signal. Sensitivity in the long wavelength tail of the spectral response curve adds appreciably to the radiation noise. Calculations by Moss show that the limiting sensitivity for a lead sulfide cell at 2.3 μ deteriorated from 5.2×10^{-14} watt at 273° K to 17×10^{-14} watt at 90° K because of the change in spectral response on cooling, the responsivity at long wavelengths being preferentially increased at low temperatures. On the other hand the limiting sensitivity at 3.5 μ for the same detector improved from 2×10^{-11} watt at 273° K to 15×10^{-14} watt at 90° K. Values quoted by Moss for the limiting sensitivity of lead telluride are of the order of 10^{-13} watt at optimum signal wavelength. There is a good measure of agreement between Fellgett's results and those of Moss. Such differences as there are should probably be attributed to differences in the characteristics of the individual detectors with which they worked.

The theoretical limit of sensitivity imposed by radiation fluctuations is, in fact, only a relative limit introduced by the assumption that a detector is always exposed to a background of room temperature radiation. Clearly, if the background radiation is a substantial source of noise, improvement may be gained by minimizing background radiation. Ideally, therefore, a detector should be used at its optimum temperature in an enclosure with walls at this same temperature. In the case of lead sulfide or lead telluride operated at liquid air temperature, the radiation field would be reduced to that of a black body at $-190°$ C, instead of 20° C, with a consequent large reduction of radiation fluctuations. Unfortunately this precaution introduces practical difficulties, because it is necessary to provide some aperture in the enclosure to admit the signal radiation. There are so far no experimental data concerning the performance of photoconductive detectors with adequate shielding, but it is reasonable to suppose that some improvement in sensitivity would be gained by cutting down the background radiation, at least to such a level that Johnson and current noise become the principal sources of detector noise. In the case of a spectroscopic application, the ideal situation would be to admit the signal radiation through a *cooled* filter. If the band pass of the filter were sufficiently narrow, the background radiation entering the detector enclosure could preseumably be reduced to an arbitrarily low level. The question of the ultimate sensitivity imposed by sources of noise other than radiation background awaits further investigation of the properties of lead sulfide and lead telluride. At present it is not possible to prescribe the optimum resistance, exciting current, or temperature for any photoconductive material. However, some progress in this direction has been made by Simpson and Sutherland (*6*), who have shown that there is a quantitative correlation between responsivity and resistance of lead telluride. This resistance is, in turn, dependent on the stoichiometric excess of lead in the photoconductive material. Moss (*7*) has correlated the spectral response with temperature for lead sulfide and lead telluride, and there is some evidence (*18*) concerning the correlation of responsivity with oxygen content of the materials.

The most interesting applications of these new detectors in pure scientific research have been in the field of infrared spectroscopy, where advances have been made in resolving power, in scanning speed, and in the observation of spectra of extraterrestrial objects. Until such sensitive detectors were available, the resolving power of an infrared spectrometer was always limited by the sensitivity of the detector and not by optical considerations. With a lead sulfide cell, Sutherland, Blackwell, and Fellgett (*19*) achieved a resolving power of over 30,000 in the water vapor spectrum near 2.5 μ. The closest pair of lines previously resolved in this region with a thermocouple detector had a separation of 0.6 cm^{-1}, corresponding to a resolving power of 7,000. More recently a lead sulfide cell has been used by the McMath Hulbert Observatory of the University of Michigan (*20*) in making a definitive map of the atmospheric absorption spectrum between 0.85 μ and 2.5 μ, in which resolving powers of over 50,000 have been achieved at various points in this range. It appears probable, therefore, that the optical limit will soon be reached, and indications that this is so are becoming evident in current work by the same group in collaboration with Mount Wilson Observatory.

It is often very desirable to be able to follow rapid changes in infrared spectra, such as occur in an explosion or in the early stages of a rapid chemical reaction. With a fast bolometer, the scanning time for a range of a few microns is of the order of several seconds (*21*), if resolving power is not to be unduly sacrificed. However, Bullock and Silverman (*22*) have shown that, by using lead sulfide, selenide, and telluride cells, it is possible to scan a range of 2 μ between 1 μ and 5 μ in a time of the order of a few thousands of a second, with a resolving power of about 100 near 3 μ, and in this way they have been able to study the initial stages of the explosive reaction between oxygen and carbon dioxide. More re-

cently Daly (*23*) has developed a similar rapid-scanning spectrometer that allows very accurate measurement to be made of the percentage absorption by using a double beam technique, which eliminates effects of atmospheric and solvent absorption.

The use of infrared spectroscopy to study the atmospheres of the planets has already given a wealth of information about the presence of carbon dioxide, ammonia, and methane on several planets (*24*). The use of photoconductive detectors will, of course, increase our knowledge of planetary atmospheres, but a new development has made possible such photoconductive detectors as the study of the reflected radiation from parts of a planet (e.g., the polar caps on Mars and the rings of Saturn). Work along these lines by Kuiper (*25, 26*) and his associates has shown that the polar caps of Mars do not consist of solid carbon dioxide and are almost certainly composed of ice. Even more interesting are the indications (*26*) that Saturn's rings may consist of ice.

In the industrial field, lead sulfide cells open up new possibilities in high-speed radiation pyrometry. Lee and Parker (*27*) pointed out that temperatures as low as 100° C can be measured with fair accuracy, and temperatures of 500° C encountered on the wheels in rapid braking of locomotives can be followed continuously with an accuracy of about 1 per cent. An obvious extension of this technique can be made to the measurement of temperature at localized hot spots in various problems in the field of friction. An entirely different application (*28*) is the use of lead sulfide cells in the cinema industry for improved sound reproduction.

References

1. SOSNOWSKI, L., STARKIEWICZ, J., and SIMPSON, O. *Nature*, **159**, 818 (1947).
2. KICINSKI, F. *Chemistry & Industry*, 54 (1948).
3. CASHMAN, R. J. *J. Optical Soc. Am.*, **36**, 356A (1946).
4. BLACKWELL, D. E., SIMPSON, O., and SUTHERLAND, G. B. B. M. *Nature*, **160**, 793 (1947).
5. MILNER, C. J., and WATTS, B. N. *Ibid.*, **163**, 322 (1949).
6. SIMPSON, O., and SUTHERLAND, G. B. B. M. *Trans. Royal Soc. (London)*, A, **243**, 547 (1951).
7. MOSS, T. S. *Proc. Phys. Soc. (London)*, B, **62**, 741 (1949).
8. ELLIOTT, A. In *Electronics*. London: Pilot Press (1947).
9. SUTHERLAND, G. B. B. M., and LEE, E. *Repts. Progress Phys.*, **11**, 144 (1947).
10. SMITH, R. A. *Semi-conducting Materials*. 198 (1951).
11. DALY, E. F., and SUTHERLAND, G. B. B. M. *Proc. Phys. Soc. (London)*, A, **62**, 205 (1949).
12. MILATZ, J. W. M., and VAN DER WELDEN, H. A. *Physica*, **10**, 369 (1943).
13. LEWIS, W. B. *Proc. Phys. Soc. (London)*, **59**, 34 (1947).
14. JONES, R. C. *J. Optical Soc. Am.*, **37**, 879 (1947).
15. FELLGETT, P. B. *Ibid.*, **39**, 970 (1949).
16. SIMPSON, O. *Proc. Phys. Soc. (London)*, **61**, 486 (1948).
17. MOSS, T. S. *J. Optical Soc. Am.*, **40**, 603 (1950).
18. GIBSON, A. F., and MOSS, T. S. *Proc. Phys. Soc. (London)*, A, **63**, 176 (1950).
19. SUTHERLAND, G. B. B. M., BLACKWELL, D. E., and FELLGETT, P. B. *Nature*, **158**, 873 (1946).
20. MOHLER, O. C., *et al. Photometric Atlas of the Near Infra-red Solar Spectrum*. Ann Arbor: University of Mich. Press (1950).
21. DALY, E. F., and SUTHERLAND, G. B. B. M. *Proc. Phys. Soc. (London)*, **59**, 77 (1946).
22. BULLOCK, B. W., and SILVERMAN, S. *J. Optical Soc. Am.*, **40**, 608 (1950).
23. DALY, E. F. *Nature*, **166**, 1072 (1950).
24. KUIPER, G. P. *Repts. Progress Phys.*, **13**, 247 (1950).
25. KUIPER, G. P., WILSON, W., and CASHMAN, R. J. *Astrophys. J.*, **106**, 243 (1947).
26. KUIPER, G. P. *The Atmospheres of the Earth and the Planets*. Chicago: Univ. Chicago Press (1949).
27. LEE, E., and PARKER, R. C. *Nature*, **158**, 518 (1946).
28. CASHMAN, R. J. *J. Soc. Motion Picture Engrs.*, **49**, 342 (1947).

News and Notes

Arid Zone Research

THE Second Session of the Advisory Committee on Arid Zone Research was held September 3–5, 1951, at Unesco House, Paris. The United Nations, the Specialized Agencies, and international nongovernmental scientific and engineering organizations with interests in arid zone research were invited to send representatives, and approximately 40 experts participated.

The session was opened by the chairman of the First Session, Richard L. Boke (USA). As chairman of the Second Session the committee elected L. Picard (Israel). The chairman designated Richard L. Boke, J. Pérès (France), and H. G. Thornton (United Kingdom) as a subcommittee to draft the report of the session.

The committee noted that the Institute of Biology (UK) was organizing in 1952 a Conference on the Biology and Productivity of Hot and Cold Deserts and recommended that its Fourth Session be held at the same place as the conference either immediately before or after it.

The committee took note of the report on the Symposium on Desert Research to be sponsored by the Research Council of Israel in 1952 and recommended that the director-general allocate a sum of $2,000 toward the publication of the proceedings of the symposium. Representatives of the Food and Agriculture Organization and Unesco reported on the exploratory mission to the Sidi Mesri Research Station, Libya. Reports were also submitted on the Saharan Research Centre, Beni-Abbes, Algeria; the Beni-Ounif Saharan Biology Station, Algeria; and the Jaswant College, Jodhpur, India.

The committee reviewed the maps showing the world distribution of arid and semiarid homoclimates prepared for Unesco by Peveril Meigs, noting that the maps had been approved by the International Geographical Union. The committee approved the list of