Title
FAR INFRARED DETECTORS

Author
Richards, P. L.

Publication Date
1970-08-01

Submitted as Chapter in book - Far Infrared
Properties of Solids - Plenum Publishing Corp.

UCRL-19690
Preprint

c. 2

FAR INFRARED DETECTORS

P. L. Richards

August 1970

AEC Contract No. W-7405-eng-48

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

34

DISCLAIMER

FAR INFRARED DETECTORS

P.L. Richards

Department of Physics, University of California, and Inorganic Materials Research Division, Lawrence Radiation Laboratory, Berkeley, California 94720

INTRODUCTION

There exist a large and growing number of useful far infrared detectors. A complete discussion of the properties of each of these detectors, including its practical and fundamental limitations, is far beyond the scope of this chapter. Fortunately, reviews do exist which present much of this material in a useful form. Of particular value are the chapter on detectors in Spectroscopic Techniques for Far Infrared, Submillimetre and Millimetre Waves[1] and large portions of The Detection and Measurement of Infra-red Radiation.[2] In this chapter some detailed information will be presented on the two far infrared detectors currently of greatest value for the spectroscopy of solids: the doped Ge bolometer and the InSb detector. In addition, heterodyne techniques, which are expected to be of increased importance in the future, will be briefly described and the superconductive Josephson effect detector will be mentioned as an example of a new development. The most commonly used far infrared detector, the Golay cell, will not be discussed since it is significantly less sensitive than the low temperature detectors and since it is sufficiently well engineered that near optimum performance can generally be achieved by simply plugging it in. Although an attempt has been made to keep this chapter self contained, supplementary reading in the above mentioned reviews is highly recommended.

THE BOLOMETER

Bolometer theory is useful not only for understanding the doped Ge bolometer, but also the InSb detector (in zero field) and other far infrared detectors such as the carbon resistance bolometer[1] and the superconductive bolometer[1]. We will first develop the general bolometer theory and then specialize it to cases of interest.

A bolometer consists of an active element characterized by a (preferably small) heat capacity C and (large) temperature coefficient of resistance $\alpha = 1/R\ dR/dT$. It is connected via a thermal link of conductance G (and small heat capacity) to a heat sink at a constant (low) temperature T_S. The resistance of the bolometer is usually[3] measured by connecting it in series with a load resistor R_L and a battery E. The voltage drop across the bolometer is then a c coupled via a capacitor to an amplifier. Since the most useful case is for $R_L >> R$, we will assume a constant bolometer current I.

The bolometer absorbs a (large) fraction ε of the incident chopped radiation signal P_1 as well as the steady background radiation P from its surroundings.[4] The power input to the bolometer is thus $\mathcal{P} = \varepsilon P + \varepsilon P_1 e^{i\omega t} + I^2R$. The bolometer responds with a temperature $\mathcal{T} = T + T_1 e^{i\omega t}$ and corresponding resistance $\mathcal{R} = R + R_1 e^{i\omega t}$. We simply require conservation of energy to obtain relations between these quantities.[5]

$$\varepsilon P + I^2R - G(T-T_s) + [\varepsilon P_1 + I^2R_1 - GT_1 - CT_1 \frac{d}{dt}]e^{i\omega t} = 0. \quad (1)$$

The static terms determine the operating temperature T while the dynamic part allows us to solve for the responsivity $S = IR_1/P_1$. We obtain[6]

$$S = \frac{\varepsilon IR\alpha}{G(1+i\omega\tau)-I^2R\alpha} \quad (2)$$

We have defined a time constant $\tau = C/G$ in the usual way.

If we neglect the second term in the denominator, (2) has a simple interpretation. The responsivity is the rate of change of bolometer voltage IR_1 with optical power P_1 focused on it. This is related by the absorptivity ε to the rate of change of voltage with temperature $IR\alpha$ divided by G the rate of change of power with temperature. The extra term in the denominator is the rate of change of bias heating power with temperature $d(I^2R)/dT = I^2R\alpha$. It is instructive to lump both terms in the denominator together so as to retain the intuitive form

$$S = \frac{\varepsilon IR\alpha}{G_e(1+i\omega\tau_e)} \quad (3)$$

where $G_e = G - I^2R\alpha$ and $\tau_e = C/G_e$ are called the effective thermal conductance and the effective time constant respectively. For a chopping frequency $\omega \ll 1/\tau_e$ the responsivity has its maximum value $S = \epsilon IR\alpha/G_e$. For higher frequencies S becomes complex (i.e., it lags the signal in phase) and its magnitude falls of as ω^{-1}.

The Germanium Bolometer

For a doped Ge bolometer operated at pumped He temperature we can assume the following properties: The resistance has the form $R \propto e^{\Delta/T}$ because of an effective semiconducting energy gap Δ, so $\alpha = -\Delta/T^2$. From the Debye law $C \propto T^3$, and for metal lead wires with impurity limited electrical conductance the Wiedemann-Franz law gives $G \propto T$. The operating temperature $T = T_s + (\epsilon P + I^2R)/G$ is determined by the absorbed steady state radiant power ϵP and the resistive heating I^2R. The former is primarily due to room temperature radiation which should be minimized by the use of cooled filters. This is much easier to accomplish in the far infrared than it is at higher frequencies.[8] (Troublesome changes in bolometer responsivity sometimes occur when a cooled solid sample is investigated because the reststrahl band in the sample significantly reduces P.) The effect of this heating can be included in an effective sink temperature $T_o = T_s + \epsilon P/G$ defined so that the operating temperature is simply $T = T_o + I^2R/G$. For a well designed far infrared bolometer T_o is very close to T_s. A practical bolometer is made large enough in area to accept the required radiation and thick enough to obtain a large value of ϵ. For this given bolometer volume the heat capacity C depends on T. The chopping frequency is selected (usually as slow as is convenient) to optimize the signal-to-noise ratio of the system and G_e is adjusted until $\omega\tau_e \simeq 1$.

A significant simplification in bolometer theory is obtained if the temperature dependence of the resistance and specific heat are expanded about the sink temperature T_o rather than the actual temperature T. Most simply we can assume that $\alpha = -\Delta/T_o^2$ and $C = AT_o^3$. This approximation is reasonable as long as $(T-T_o)/T$ is small. We may neglect the distinction between dynamic and static thermal conductance[5] for the same reason. Using $G_e = G[1-\alpha(T-T_o)]$ we find

$$S = \frac{-\epsilon\Delta}{(1+i)}\sqrt{\frac{R\,(T-T_o)}{\omega A T_o^5[T_o^2 + \Delta(T-T_o)]}} \qquad (4)$$

Clearly, to maximize the responsivity the sink temperature T_o must be made as low as possible. The bolometer current I, which is the most easily accessible variable is adjusted for the optimum operating temperature. The important features of (4) to keep in mind are that S varies directly as the square root of the bolometer resistance R and inversely as the square root of the chopping frequency ω and the bolometer volume or the heat capacity constant A, The theory of the doped Ge bolometer has been developed in various approximations[3] by different authors, but these conclusions remain the same.

Bolometer Materials

Bolometers can be made from Ge doped with sufficient impurities that conduction occurs in the He temperature range by the hopping process. In this range, an effective gap Δ exists which is a small fraction of the donor or acceptor energy, and far infrared radiation is strongly absorbed due to photo-excitation of bound carriers. Gallium doped Ge with a room temperature resistivity of $0.11 < \rho < 0.13$ ohm-cm and In doped Ge with $\rho \simeq 0.06$ ohm-cm have been used successfully by the author at pumped He^4 temperatures. The properties of a bolometer made from this latter material are given in Table I. Germanium doped with $6\times10^{16}/cm^3$ In and $2.4\times10^{16}/cm^3$ Sb has been used very successfully by Drew and Sievers[11] for a bolometer operated at pumped He^3 temperatures as shown in Table I. The pioneering article by Low[10] gives the properties of a Ga doped bolometer.

Bolometer	Richards	Drew and Sievers
Impurity	Primarily In	In and Sb
Bolometer volume	$4.5 mm^3$	$8 mm^3$
Resistance R	1×10^5 ohm	1.5×10^6 ohm
Effective gap Δ	$\sim 14^\circ K$	$3.9^\circ K$
Sink temp. T_s	$1.1^\circ K$	$0.37^\circ K$
Bolometer temp. T	$1.5^\circ K$	$0.43^\circ K$
Thermal conductance G	$5\times10^{-5} W/^\circ K$	$8\times10^{-8} W/^\circ K$
Time constant τ	5×10^{-3} sec	10^{-2} sec
Responsivity S	$4\times10^4 V/W$	$2\times10^6 V/W$
RMS noise V_n	$3.6\times10^{-8} V/\sqrt{Hz}$	$5.3\times10^{-8} V/\sqrt{Hz}$
Noise equivalent power NEP	$9\times10^{-13} W/\sqrt{Hz}$	$3\times10^{-14} W/\sqrt{Hz}$

Table I. Properties of two doped Ge bolometers. The bolometer materials were selected in each case for good performance at the sink temperature chosen. The advantage of low T_s is clearly shown.

Unfortunately no systematic study of the low temperature electrical properties of heavily doped Ge has been carried out[12] so the selection of bolometer materials remains an art. It does appear that R and Δ can be varied somewhat independently by using compensated material with two types of impurity. For reproducible results it is very important to work with pure starting material and take care that the doping is homogenous. Variations in

Responsivity $\dfrac{9\times10^{-13} W/\sqrt{Hz}}{5\times10^{-5} W/{}^\circ K} = \underline{2\times10^{-8}\ {}^\circ K/\sqrt{Hz}}$

impurity concentration cause much larger changes in He temperature than room temperature properties.

Very little has been published about the far infrared absorption of bolometer materials in the operating temperature range. It does appear that care must be taken to obtain adequate absorption at long wavelengths.[12,13] About 30 percent reflectance is expected in the far infrared from the low frequency lattice dielectric constant of Ge. Systematic measurements of absorptance as a function of doping (including compensation) would be of value for a fundamental understanding of hopping conductivity as well as for bolometer construction.

Bolometer Mounting

The bolometer must be mounted in a vacuum (or in a He exchange gas to provide thermal conductance to the sink) in such a way that the infrared signal can be efficiently absorbed. Two types of mounting are commonly used. Commercial detectors are usually sold in a metal optical Dewar with cooled windows designed to accept a focused beam. A somewhat cheaper and more flexible system used by the author and many others who make their own bolometers is to place the bolometer at the exit of a focusing cone which is fed from a metal light pipe[14] entering the top of a dewar. The bolometer is surrounded by a sealed integrating cavity as shown in Fig. 1.

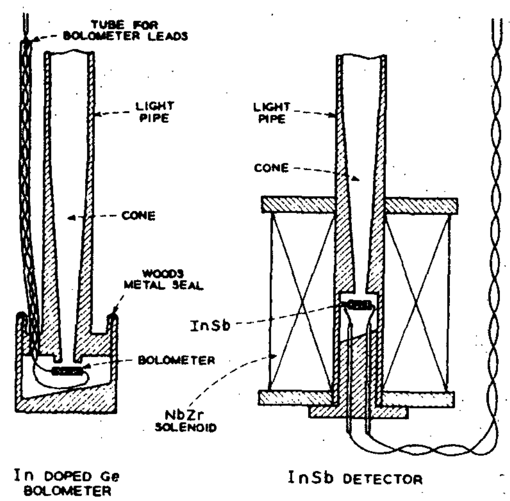

Fig. 1. A widely-used mounting for He temperature far infrared detectors. The assemblies are made from brass and immersed in liquid helium in a conventional glass cryostat. The Ge bolometer is operated in a vacuum while the InSb detector is immersed in liquid He. Each detector is backed by an integrating cavity[15] to enhance absorption.

The metal bolometer leads are generally attached to the carefully etched bolometer element by an In solder, and clamped to the bottom of the focusing cone to provide both mechanical support and a thermal link to the He bath. This system has about the same optical efficiency as the commercial one, but uses inexpensive conventional Dewars and can be readily combined with a variety of mountings for cooled samples as shown[16,17] in Figs. 2-3. A sealed He temperature window is often desirable in the design of such systems.

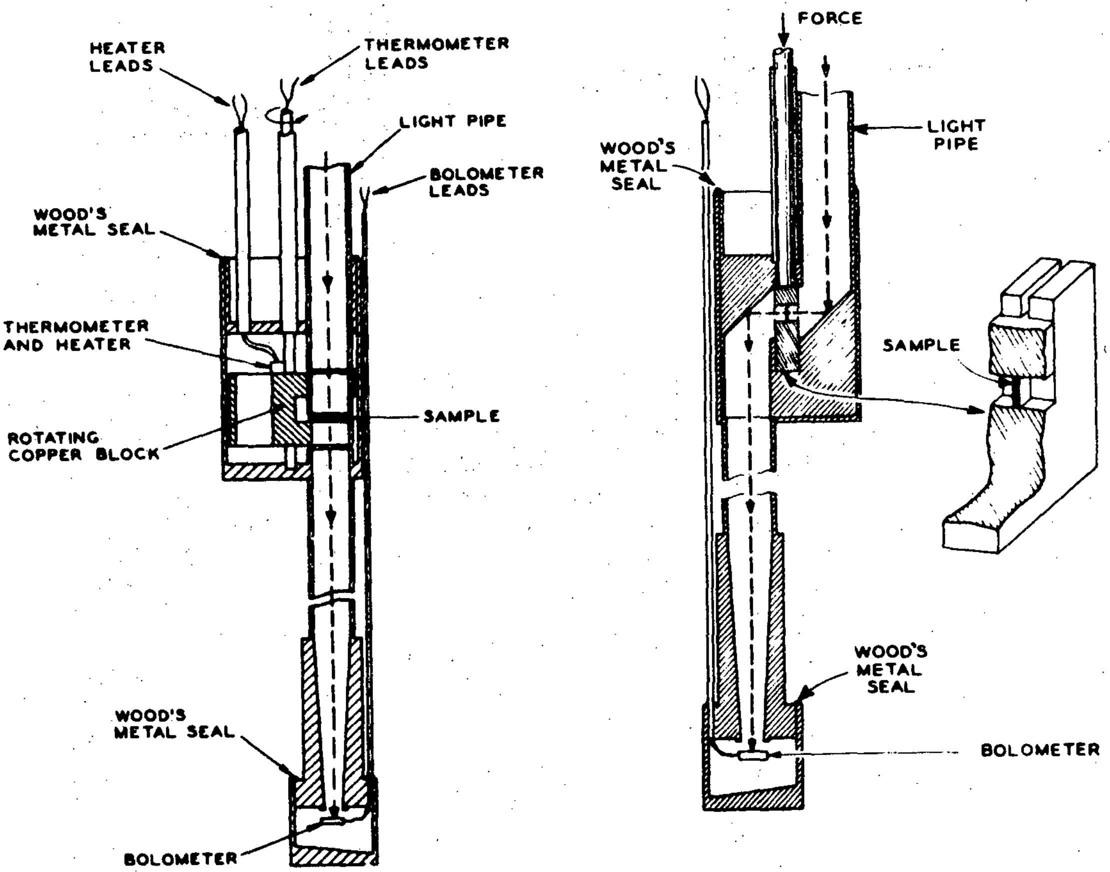

Fig. 2. Apparatus for measuring the transmittance of samples as a function of temperature[16] and uni-axial stress. The sample chamber in each case is evacuated. If sample temperature must be measured precisely it is preferable to mount sample in liquid He or in a He exchange gas.

It is used to isolate the detector vacuum space from a sample chamber filled with He. A sapphire disc made wedge shaped to avoid interference fringes and brazed to a metal ring[18] is reasonably transparent at low temperatures from 2-250 cm^{-1} and absorbs a considerable fraction of the higher frequency room temperature radiation.

Bolometer Testing

It is possible to measure the responsivity of a bolometer (aside from the absorptivity ε) by purely electrical means. All that is required is to introduce a known electrical heating power

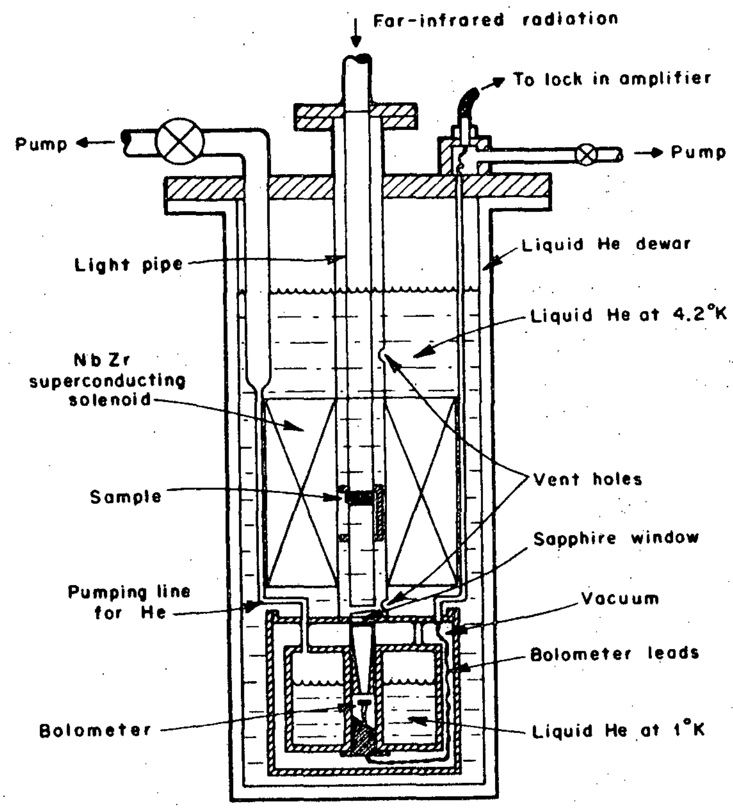

Fig. 3. Apparatus for measuring the transmittance of samples as a function of magnetic field.[17] Samples can be interchanged with minimal loss of He and, by closing the vent holes, the sample chamber can be evacuated for measurements at temperatures above 4.2°K.

at the proposed modulation frequency and to measure the ac voltage response. Practical methods for doing this are discussed in an article by Jones.[7] Anyone seriously interested in using bolometer detectors should be prepared to take these simple measurements. Accurate measurements of noise power require the use of an rms voltmeter and careful attention to bandwidths, but "eyeball" estimates are usually adequate for comparing detectors and for locating optimal operating conditions.

Amplifier

A lock-in phase sensitive amplifier is always used to provide adjustable integrating bandwidth around the chopping frequency. An ideal amplifier for use with the doped Ge bolometer should make a negligible contribution to the system noise. The amplifier noise usually arises from the first stage of amplification and often has a power spectrum $\propto \omega^{-1}$ in the frequency range most useful for Ge bolometers. The quality of a prospective preamplifier can best be judged by connecting a He temperature resistor equal to the bolometer resistance R to the input. A very good amplifier system can see Johnson noise at $\sim$30 Hz from a 10^6 ohm resistor at 4.2°K. The author has found that amplifiers based on the 6CW4 nuvistor tube are usually superior at low frequencies to those using field-effect transistors.

Bolometer Noise

In many experiments the most important criterion for the usefulness of the detector is the minimum value of signal power which can be detected. This is usually called the noise-equivalent power (NEP). In most low temperature thermal detectors there are several important contributions to the observed noise. It is often rather tedious to determine which contributions are dominant under a given set of operating conditions. In order to minimize the noise, however, its source must be identified. The sources of noise in a low temperature bolometer in a bandwidth B Hz centered about a frequency $\omega < 1/\tau$ can be written[19]

$$(\mathrm{NEP})^2 = \frac{4kTRB}{S^2} + 4kT^2GB + 8\varepsilon\sigma kAT_R^5B\sin^2\left(\frac{\phi}{2}\right) + \frac{CI^{\alpha}B}{\omega^{\beta}S^2} \qquad (5)$$

where each term is given in the form of the square of an optical noise power incident on the bolometer. The first term is the Johnson or Nyquist noise associated with the bolometer resistance R. Since $S \propto R^{1/2}$ this noise contribution is independent of R. The second term is the noise from statistical fluctuations in the bolometer temperature. At frequencies $\omega \gtrsim 1/\tau$ this term falls[2] off as $(1+i\omega\tau)^{-1}$. It is a minimum for slow (small G) bolometers. The third term arises from the statistical fluctuations in the black body radiation which strikes the bolometer of area A from a background temperature T_R viewed through a cone of angle ϕ. This term must of course be modified to include the effects of any cooled filters which limit the background radiation.[19] Typical values[1] are 10^{-13} to 10^{-14} W. The last term summarizes other possible contributions to the noise such as current noise in the bolometer, or current-independent inverse frequency flicker noise power from the amplifier. In a practical far infrared bolometer the last three terms in (5) may be of comparable magnitude so that careful study is required to determine the optimal operating conditions.[20] It appears possible to reduce bolometer current noise to a negligible value[10] by the use of single crystal material and careful attention to the method of making electrical contacts. It is usually the NEP and not the responsivity which determines the usefulness of a detector system. There may even be circumstances under which reducing S would improve system performance. In most spectroscopic applications the chopping frequency is selected to minimize the NEP. If the system noise is dominated by the last term in (5) with $\beta > 1$, then a high frequency bolometer is desirable. For all other cases ω should be chosen as small as practical. A commonly used value is 10Hz.

An ideal low temperature thermal detector for a given application is one which is limited by fluctuations in <u>unavoidable</u> background radiation. This condition can be met by broad band detectors in the near infrared,[10] but there is considerable room for improvement in the far infrared.

THE InSb DETECTOR

The InSb detector is sometimes called a photoconductive detector and sometimes an electronic bolometer. The reason for the variety in nomenclature is that under various operating conditons the parameters which describe the behavior of the charge carriers in the InSb, such as the plasma frequency, the cyclotron frequency, the impurity depth, and the photon energy can be the same order of magnitude. Therefore, few of the usual simplifying assumptions are made in the theoretical description of the detector. The InSb detector used by the author is a block of n-type material with a carrier density of $\sim 10^{14}/cm^3$. The leads are attached with In solder and it is mounted in a NbZr superconductive solenoid as shown in Fig. 1.

It is helpful to think of the indium antimonide detector as an electronic bolometer. Because of a relatively long electron-lattice relaxation time of 10^{-6} to 10^{-7} sec the electrons are the active element and the lattice, which is cooled by immersion in liquid helium, acts as a thermal sink. When the carriers absorb radiation, their temperature rises relative to the lattice and, because their mobility is limited by ionized impurity scattering, the resistance of the bolometer drops.

In zero magnetic field the carriers absorb photons in the neighborhood of the plasma and relaxation frequencies. In a magnetic field, absorption also occurs at the cyclotron resonance frequency. The magnetic field has a second important effect. In zero field the impurity centers in the n-type indium antimonide overlap so that the impurity energy levels merge into the conduction band. The conductivity thus lacks the exponential temperature dependence characteristic of most semiconductors. In a magnetic field the impurity centers contract and separate impurity levels develop. At low temperatures, therefore, a magnetic "freeze-out" of carriers occurs causing the large resistivity illustrated in Fig. 4. Measurements of the responsivity of this detector relative to an In doped Ge bolometer are shown in Figs. 4. and 5. In general, the responsivity is higher at pumped helium temperatures and in a magnetic field. The broad region of responsivity which falls off with frequency can be interpreted as absorption by the carriers in the vicinity of the plasma and relaxation frequencies.

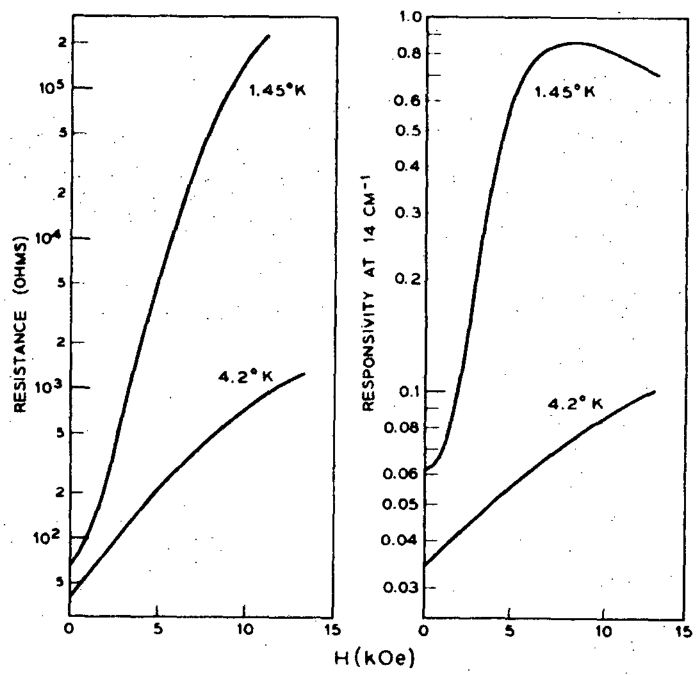

Fig. 4. Magnetic field dependence of resistance and responsivity (KV/W) of an InSb detector.[13] The bias current was set for minimum NEP.

Two peaks in responsivity are also seen near the cyclotron frequency, which is proportional to magnetic field. This observed splitting of the cyclotron resonance peak shows that our electronic bolometer model is oversimplified. The peaks are actually due to transitions between impurity states with different angular momenta associated with the first and second Landau levels. Thus the InSb detector in a magnetic field (Putley detector) does not show strictly cyclotron resonance response. Since it involves transitions between impurity levels with a consequent change in carrier mobility, the Putley detector is often referred to as a photoconductive detector.

The complicated spectral response of the InSb detector can be used to advantage in certain experiments. When experiments are done in the range $\omega \lesssim 50$ cm^{-1} using an Hg arc source the relative insensitivity of the InSb detector operated at low fields to higher frequency radiation greatly simplifies filtering problems. At higher frequencies the peak in detector sensitivity at approximately the cyclotron resonance frequency $eB/m^{*}c$ shown in Figs. 5. and 6. can be used as an order sorter for a grating monochromator or even by itself as a low resolution monochromator. The width of the cyclotron resonance peak depends on the thickness of the detector and can be made somewhat narrower than shown in Fig. 6.

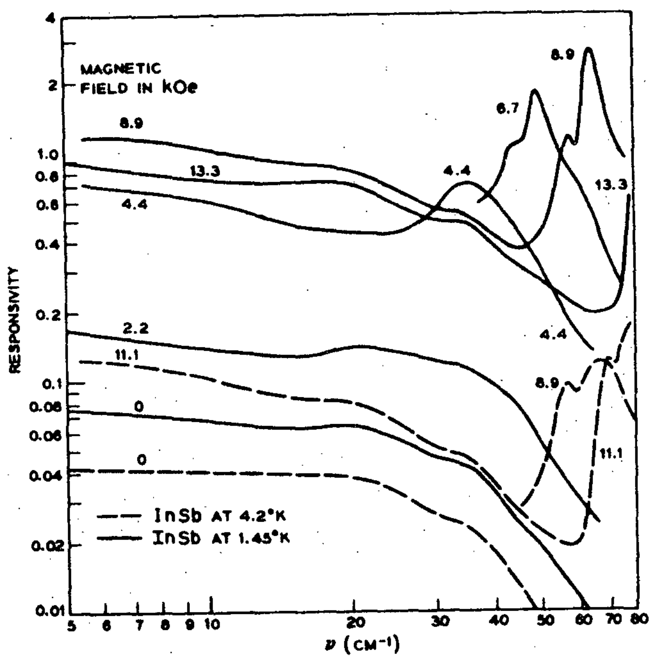

Fig. 5. Frequency dependence of the responsivity (inKV/W) of an InSb detector[13] for various values of temperature and magnetic field.

Sources of Noise

As is the case with the Ge bolometer, the InSb detector current is selected to minimize its NEP. The maximum useful current is often limited by noise arising from avalanche breakdown in the detector.

Because of its relatively low responsivity the InSb detector is usually amplifier noise limited. The strong variation of resistance with field makes it desirable to have several amplifier input impedances available. Fig. 4. shows that the square of the voltage responsivity of the InSb detector falls less rapidly than its resistance[21] as H is decreased. Therefore, if the detector is matched to the amplifier with an ideal noise-free transformer, optimum performance would occur at $H = 0$. Excellent results[1] have been obtained by using a transformer cooled to He temperatures. There is some evidence that the relation between responsivity and impedance, which determines the optimum operating point of the detector, varies somewhat between different indium antimonide samples.

The InSb detector has similar fundamental noise limitations from Johnson and background radiation noise to those given in (5) for the Ge bolometer. It is, however, expected to have temperature fluctuation noise only under those conditions for which it is primarily an electronic bolometer[22].

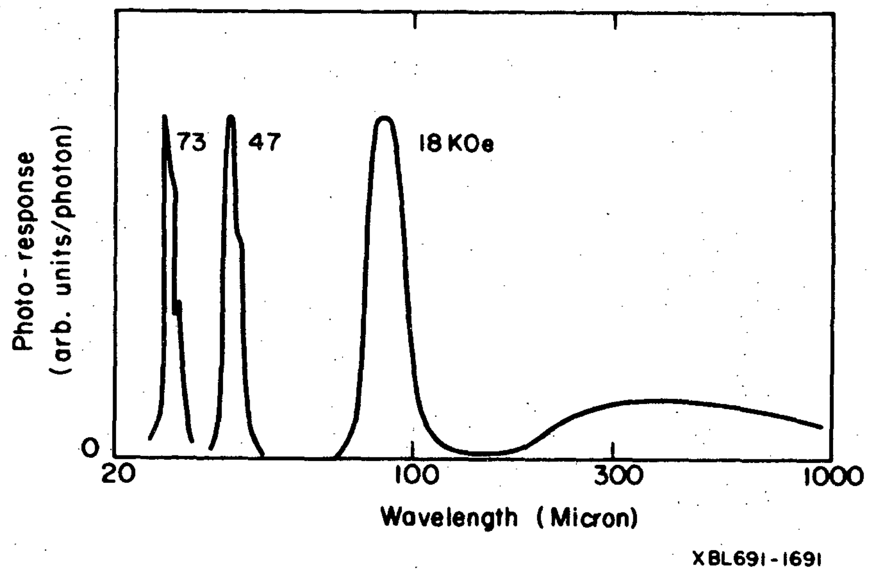

Fig. 6. Performance of the tunable InSb detector[1]

Speed of Response

The electron lattice relaxation time for low carrier density InSb is in the range from 10^{-6} to 10^{-7} sec under various conditions of temperature and magnetic field.[1] The electric bolometer is thus, of necessity, very fast. It is difficult to chop a continuous source of far infrared at frequencies much above 1 KHz but this is adequate to get above the low frequency flicker noise in most amplifiers. The InSb detector is particularly useful with pulsed radiation sources such as lasers or unstable plasmas. One difficulty encountered in actually using the potential fast response of the InSb detector is that cable and amplifier input capacitance reduces the input impedance below the detector resistance thus shorting out high frequency signals. One solution to this difficulty is to bias the detector with a constant voltage and use an amplifier in series with it connected as a low input impedance current detector. System response times of 10^{-6} sec have been obtained in this way.

HETERODYNE TECHNIQUES

The square law detectors described in the preceeding sections are often limited by noise associated with their wide spectral bandwidth. If all of the signal information is confined to a narrow infrared band as is the case with a laser spectrometer, the sensitivity can be increased by mixing the signal with a local oscillator (laser) in a square law detector and then observing the difference frequency in a finite bandwidth.[1] The total electric field vector at the detector is due to the signal plus the local oscillator. If the signals arrive in phase we have

$$E = E_s \cos \omega_s t + E_{LO} \cos \omega_{LO} t . \qquad (6)$$

The detector response r is proportional to E^2 so (7)

$$r \propto E_s^2 \cos^2 \omega_s t + E_{LO}^2 \cos^2 \omega_{LO} t + E_s E_{LO} [\cos (\omega_s - \omega_{LO}) t + \cos (\omega_s + \omega_{LO}) t]$$

Because of its finite bandwidth the detector cannot follow the infrared frequencies. It is assumed to be able to respond at the intermediate (IF) frequency $\omega_s - \omega_{LO}$ so the detector output is simply

$$r \propto E_s E_{LO} \cos (\omega_s - \omega_{LO}) T + \text{constant}$$

Measurement of the signal is confined to a bandwidth B about the intermediate frequency so

$$r_{IF} = E_s E_{LO} \cos (\omega_s - \omega_{LO}) t \qquad (9)$$

One advantage of this method is immediately apparent when we compare (9) with the response $r \propto E_s^2$ of the same detector operated in the conventional (video) manner. If the local oscillator is strong, $E_{LO} >> E_s$, then a much larger signal is obtained. The NEP for such a system may be correspondingly lower. In the heterodyne receiver using a phase sensititve detector only the noise in the post detection bandwidth B is important. For example, the noise power NEP $\approx kTB$ when $h\nu << kT$ can be 4×10^{-21}W in a one Hz bandwidth for T = 300°K. In a square law video detector the effective noise bandwidth is the geometric mean of B and the (much larger) spectral sensitivity range.[23] Heterodyne detection promises to become more common in the far infrared, especially with laser spectrometers. Already many far infrared detectors (including the lowly Golay Cell) have been operated in heterodyne systems.[1]

JOSEPHSON EFFECT DETECTOR

As an example of a recently developed far infrared detector we now consider the superconducting Josephson effect detector. Although it is in a very early stage of development, it has several useful properties which make it appear promising. These include high sensitivity, extremely high speed, and potential as a tunable narrow band detector.

The Josephson effect, the tunneling of a lossless supercurrent through an oxide barrier separating two superconductors is one of the most complicated and interesting phenomena of modern solid state physics. An elementary review of these phenomena is available.[24] For the present discussion we need only observe that the current flow through such a junction has the form

$$I = I_o \sum_{n=-\infty}^{\infty} J_n \left(\frac{2eV_1}{\hbar\omega_1}\right) \cos\,(\omega_o + n\omega_1)t \qquad (11)$$

Where J_n is Bessel's function of order n, ω_o is the Josephson frequency, ω_1 the rf frequency and V_1 the rf voltage. When operating a Josephson junction as a detector we observe the dc (or near dc) component of this current flow which occurs when $\omega_o = n\omega_1 = 0$.

Broad Band Detector

When the detector is biased so as to observe the zero voltage current at $2eV_o/\hbar = \omega_o = 0$ then the dc component of (11) occurs for n = 0 and is thus independent of the rf frequency ω_1. A detector has been operated in this mode[25] using a point contact Josephson junction fabricated by simply touching two Nb wires together at liquid He temperatures. Broad band sensitivity was observed extending to ≈ 40 cm^{-1}. In favorable cases an NEP of 5×10^{-14} W/$\sqrt{\text{Hz}}$ could be achieved. Unlike a bolometer the sensitivity is expected to be independent of response frequency up to 10^{11} Hz.

Narrow Band Detector

If the detector is biased at a finite voltage then dc current flows for $\omega_o = n\omega_1$. Unfortunately, however, the amount of current flow is negligible for small V_1 since $J_n(\chi) \propto \chi^n$ for small χ. Thus, J_o is finite for small V_1, but not J_n for $n > o$. This difficulty can be avoided, however, if the detector is operated in a cavity which is resonant at ω_o. If the junction is biased at the constant voltage $V_o = h\omega_o/2e$ then the ac Josephson current will excite the cavity mode. Under these circumstances, there is a large V_1 and a large dc current flowing. An additional V_1 due to radiation coupled into the cavity will cause a large change in the dc current and will thus be detected. This situation is exactly analogous to a regenerative radio receiver. The receiver bandwidth is much narrower than the Q of the tuned circuit which controls the feedback.

A detector has been operated in this mode which has remarkable properties.[26] The detection bandwidth as shown in Fig. 7. is too small to be measured by the techniques of Fourier transform spectroscopy. An upper limit of $\delta\nu = 10^{-2}$ cm^{-1} has been established.

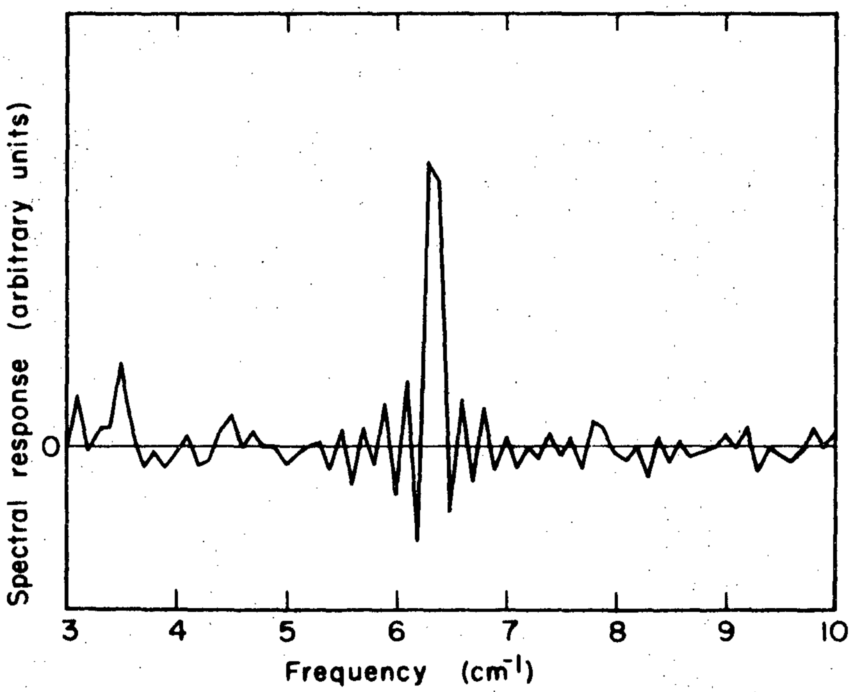

Fig. 7. Spectral response of regenerative Josephson effect detector[25] as measured with spectrometer with a $(\sin\nu)/\nu$ spectral window function.

Assuming this bandwidth the observed NEP is conservatively estimated to be 10^{-14} W/$\sqrt{\text{Hz}}$. If the bandwidth is actually narrower, the NEP is proportionally smaller. Since it is a square law detector, the effective noise bandwidth of this narrow band detector is $\sqrt{\delta\nu B}$.[23] The fundamental limit set by photon shot noise to the measurement of a monochromatic signal is NEP $\simeq 2h\nu\sqrt{\delta\nu B} \simeq 10^{-18}$W. The improvement over the fundamental limits for the Ge bolometer or the InSb detector is due entirely to the smallness of $\delta\nu$.

Josephson effect detectors are in a very primitive state of development at the present time, but show promise for the future. For example, in the proper type of cavity several resonances couple to the junction. The frequency of the detector can then be voltage tuned from one resonance to another. In principle the cavity dimensions can be changed so that the detector frequency could be swept continously. Such a detector, when used with a black body source, would eliminate the need for a monochromator or interferometer in the difficult 2 - 30 cm $^{-1}$ frequency range.

REFERENCES

1. Spectroscopic Techniques for Far Infrared, Submillimeter and Millimeter Waves, D. H. Martin, ed., (North Holland Publishing Company Amsterdam, John Wiley and Sons, Inc., New York, 1967).

2. The Detection and Measurement of Infrared Radiation, R.A. Smith, F.E. Jones, and R. P. Chasmar. (Oxford, 1968) 2nd ed.

3. A bridge circuit is sometimes used with a bolometer in each of two legs in order to cancel out the effect of a drift in the temperature T_S. In this case radiation is allowed to hit only one of the bolometers.

4. For He temperature bolometers we can neglect the power radiated by the bolometer, as well as the noise generated by fluctuations in this radiation.

5. More exactly, it is the dynamic thermal conductance dP/dT which appears in the dynamic terms of (1) and the static conductance G which determines the operating temperature T. See Ref. 2 for a detailed discussion.

6. If the load resistor R_L is not >>R then the responsivity will be multiplied[2] by the bridge factor $R_L/(R_L+R)$ and the bias heating power term $I^2R\alpha$ in the denominator of (2) by $(R_L-R)/(R_L+R)$. The responsivity may be singular if the two terms in the denominator of (2) cancel. This may occur when $\alpha > 0$ and $R_L > R$ because an increase in T increases R and thus increases the power dissipated in R from a high impedance source. It can also occur when $\alpha < 0$ and $R_L < R$ because an increase in T decreases R and increases the power dissipated in R from a low impedance source. These instabilities which rarely cause difficulty for low temperatures bolometers are discussed extensively by Jones.[7]

7. R. C. Jones, J. Opt. Soc. Am. 43, 1 (1953).

8. Useful filters for this purpose are described by Y. Yamada, A. Mitsuishi and H. Yoshinaga, J. Opt. Soc. Am. 52, 17 (1962).

9. A somewhat better approximation than that used here is desirable if an accurate value of the optimal operating temperature T is to be calculated. Rather than use the exponential dependence of R(T) assumed here, Low[10] has introduced the form $R = R_o(T_o/T)^4$ which has some calculational advantages.

10. F. J. Low, J. Opt. Soc. Am. 51, 1300 (1961).

11. H.D. Drew thesis, Cornell University, 1968.

12. A start in this direction has been made by S. Zwerdling, R.A. Smith, and J.P. Therrault (to be published).

13. P.L. Richards, Pure and Appl. Chem. 11, 535 (1965).

14. R. C. Ohlman, P. L. Richards and M. Tinkham, J. Opt. Soc. Am. 48, 531, (1958).

15. The integrating cavity can be analyzed from the theory of W.E. Lamb, Jr., Phys. Rev. 70, 308 (1946).

16. P.L. Richards, Phys. Rev. 138, A1769 (1965).

17. R. R. Joyce and P.L. Richards, Phys. Rev. (to be published 1969).

18. Availably commercially from Eimac Co., 301 Industrial Way, San Carlos, California.

19. F.J. Low and A. R. Hoffman, App. Optics 2, 649 (1963).

20. For this reason the concept of specific detectivity D* is often not useful for Ge bolometers.

21. More precisely, it is the differential detector resistance dV/dI, not R = V/I, which is important for matching to the amplifier, In the operating range dV/dI ≃ R/2 for the indium antimonide detector.

22. E. Putley, Infrared Phys. 4, 1, (1964).

23. R. A. Smith, Proc. Inst. Electrical Eng. 98, 43 (1951)

24. P.L. Richards, Sidney Shapiro, and C. C. Grimes, Am. J. Phys. 36, 690 (1968).

25. C. C. Grimes, P.L. Richards and S. Shapiro, Phys. Rev. Letters 17, 431 (1966), and J. Appl. Phys. (to be published).

26. P.L. Richards and S. A. Sterling (to be published).