DEVELOPMENTS IN THE DETECTION OF FAR INFRARED RADIATION

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INTRODUCTION

The sensitivity available from far infrared spectroscopic systems has increased rapidly in recent years. This improvement is partly due to the introduction of interference techniques and of laser or microwave harmonic sources, but also to the development of liquid helium temperature detectors.

Our discussion of this broad subject must necessarily be selective. Only those detectors which are most useful in the frequency range from 10–100 cm^{-1} will be included. This restriction does not imply that the detectors and techniques described here are not useful outside this range, but that other techniques become competitive at higher and lower frequencies. The problems of time-resolved spectroscopy will not be considered, so detector sensitivity will be assumed to be more important than speed. The superconducting bolometer will be arbitrarily eliminated from this discussion because of the author's lack of personal experience with it. Though more difficult to construct than the detectors discussed here, it appears capable of performance comparable to the best of them[1].

Three of the most useful detectors for the 10–100 cm^{-1} range are the carbon resistance bolometer, the doped germanium bolometer, and the indium antimonide detector. The latter two are becoming available commercially, but not in a form that guarantees optimum performance for the user. The purpose of this paper is to provide practical information useful to those who wish to build and/or use such detectors. The physical principles on which they operate, which are imperfectly understood in some cases, will not be emphasized.

BOLOMETERS

The carbon resistance bolometer of Boyle and Rodgers[2] was an outgrowth of the use of carbon resistors as thermometers at liquid helium temperatures. The advantages of doped germanium thermometers[3] subsequently led several laboratories to develop doped germanium bolometers. The first published report was by Low[4].

A simple model can be used to describe the optimum operating conditions of such bolometers. Let us assume that an infrared signal chopped at frequency ω is absorbed in a bolometer of specific heat c. The bolometer is attached by a thermal conductance κ to a thermal bath at T_B. If the total power input to the bolometer is $P_0 + P_1e^{i\omega t}$, it will respond with a thermal time constant $\tau = c/\kappa$ giving a temperature $T_0 + T_1e^{i\omega t}$ and electrical resistance $R_0 + R_1e^{i\ t}$. The resistance of both carbon and germanium bolometer materials in the helium range is well approximated by $R = A \exp (\Delta/T)$, so that:

$$R_1 = -\frac{R_0 \Delta T_1}{T_0^2} = \frac{-R_0 P_1 \Delta}{\kappa\left(T_{\mathrm{B}} + \frac{P_0}{\kappa}\right)^2 (1 + \mathrm{i}\omega t)} \tag{1}$$

When a constant bias current I is supplied, the alternating signal voltage IR_1 will increase with I until T_0 begins to rise appreciably because of the contribution of I^2R_0 to P_0†. All other contributions to P_0, such as room temperature black-body radiation, must be minimized. Clearly, Δ and R_0 must be large and T_{B} small to obtain maximum responsivity $\mathscr{R} = IR_1/P_1$. Subject to the restriction that we want $T_{\mathrm{B}} \approx P_0/\kappa$, it is desirable to have κ small. Since $\tau = c/\kappa$, optimum responsivity is obtained with relatively slow bolometers. In practice, we make c as small as possible and adjust κ to obtain a convenient low operating frequency $\omega = 1/\tau$. For much larger κ, the responsivity $\mathscr{R} \propto \omega^{-1}$. If the effective noise power of the system varies as ω^{-1}, as is often the case when amplifier noise predominates, then the voltage signal-to-noise ratio varies as $\omega^{-\frac{1}{2}}$ and a slow detector is still desirable.

Using these simple considerations as a guide, the author has constructed and used a large number of far infrared bolometers from carbon resistors and from various kinds of doped germanium. All of these detectors have been mounted in evacuated cavities at the end of a 1 metre long 1·1 cm i.d. light pipe as shown in *Figure 1*. The cavities and part of the light pipe are immersed in pumped liquid helium so that $T_{\mathrm{B}} = 1{\cdot}0$–$1{\cdot}2$°K. Such light pipes are efficient and convenient for far infrared use[6] and, when lined with camphor soot or used with cooled low pass filters, help to reduce the contribution of room temperature radiation to P_0. It is worth noting that bolometers made for use at frequencies higher than 100–200 cm^{-1} cannot tolerate such filtering and are consequently less sensitive.

The representative carbon resistance bolometer shown in *Figure 2* is an 0·3 × 5 × 7 mm slice cut from a 50 Ω, 2 W Allen Bradley resistor (100 Ω, 0·5 W resistors are also used when smaller bolometers are desired). The electrodes are electro-deposited copper, and the thermal conductance to the bath is provided by gluing the back of the bolometer to a metal post with General Electric 7031 varnish, using a 0·5 mill thick mylar film for electrical insulation. This bolometer has $\Delta = 8$, $R_0 = 30$ kΩ, and $\tau = 10^{-2}$ sec when $I = 10^{-4}$ A, $T_0 = 2{\cdot}8$°K and $T_{\mathrm{B}} = 1{\cdot}2$°K. In general, carbon resistance bolometers show current noise which is large compared with the noise from a good amplifier and are thus *less* useful than the doped germanium bolometer.

The representative doped germanium bolometer shown in *Figure 2* is a 0·25 × 4 × 4 mm slice cut from indium doped germanium which has a room temperature resistivity of 0·06 ohm-cm. The slice was thoroughly etched and 0·18 mm diameter copper leads attached with indium solder. The leads, which furnished the thermal contact to the bath were glued in a

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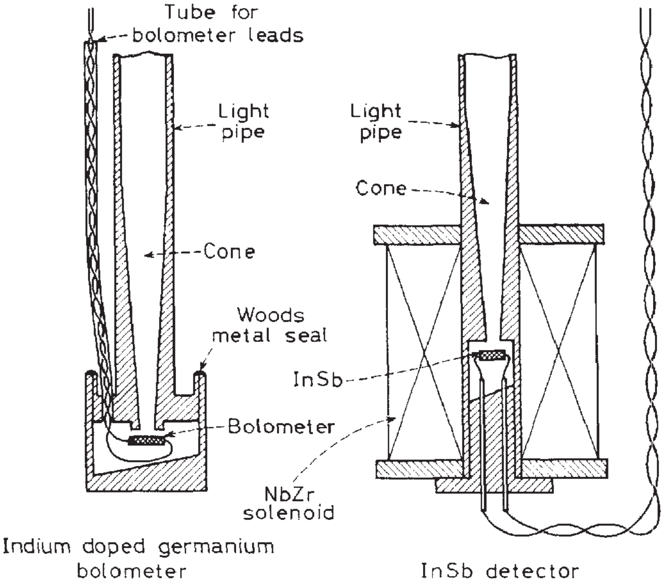
† In order to simplify the analysis presented here, terms in I^2R, have been neglected. Under typical operating conditions these may change the predicted responsivity and time constant by the order of 10 per cent. For a complete analysis see Jones[5].

hole in a brass heat sink about 1 cm from the bolometer. This bolometer had $\Delta = 14$, $R_0 = 140$ kΩ, and $\tau = 6 \times 10^{-3}$ sec when $I = 5 \times 10^{-5}$ A, $T_0 = 1{\cdot}9$°K, and $T_B = 1{\cdot}0$°K. Arsenic doped germanium bolometers have also been used by the author. In this case the leads were attached with tin–lead solder doped with arsenic to avoid the formation of *p-n* junctions. Low[4] has used gallium doped germanium and Wheeler[7] gallium arsenide, for which Δ is especially large. Estimates of the room temperature resistivity of the required material can be obtained from the literature[8], but it should be



Indium doped germanium bolometer

InSb detector

Figure 1. Typical mounting for far infrared helium temperature detectors. The assemblies shown were made from brass and immersed in liquid helium in a conventional glass cryostat. The cavity gives radiation transmitted through the detector a second chance to be absorbed. The carbon and germanium bolometers are operated in vacuum while the indium antimonide detector is immersed in liquid helium

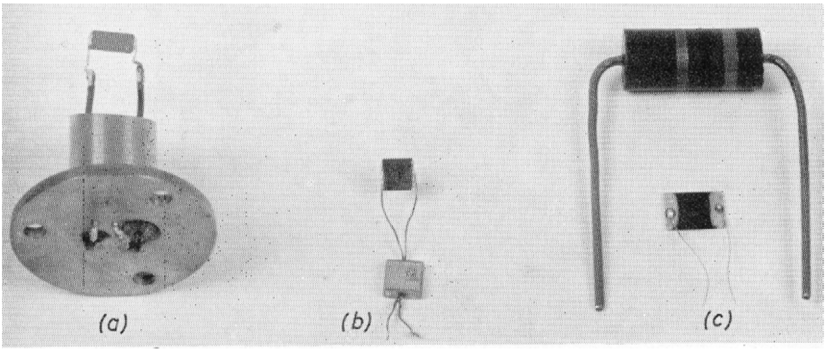


Figure 2. Photograph of three types of liquid helium temperature far infrared detectors. (*a*) Indium antimonide. (*b*) indium doped germanium. (*c*) carbon

emphasized that only an extremely narrow range of impurity is useful; Too much, and Δ vanishes; too little, and the bolometer doesn't absorb radiation effectively. The most useful procedure is to obtain a boule of germanium with a range of impurity concentration and locate the useful region by resistivity measurements at low temperatures.

Measurements of the relative responsivity of germanium and carbon bolometers are shown in *Figure 3*. The observed frequency dependence arises from the fact that not all the radiation incident on the bolometer is absorbed. Transmissivity measurements at temperatures near T_0 showed that neither bolometer transmits appreciably above 25 cm^{-1}, but that by 5 cm^{-1} the carbon bolometer transmitted 47 per cent and the germanium bolometer 32 per cent of the incident radiation. The roll-off in responsivity expected from this low frequency transmissivity is reduced by mounting the bolometer in a cavity or on a reflecting backing, but it may account for the observed roll-off in the relative responsivity of the carbon bolometer at low frequencies in *Figure 3*. Measurements of bolometer reflectivity at T_0 proved difficult, but measurements at higher temperatures on carbon and calculations for germanium indicate that the reflectivity is probably dominated in each case by lattice effects. The calculations were based on carrier densities

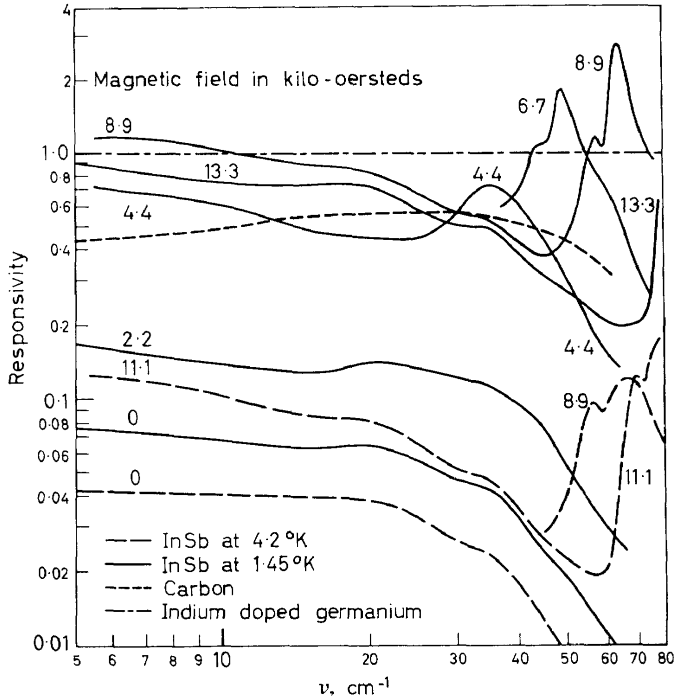


Figure 3. Measured responsivity of indium antimonide and carbon far infrared detectors relative to that of an indium doped germanium detector. The responsivity of the indium doped germanium bolometer, which is expected to be reasonably independent of frequency, is assigned the value unity. Bias current was chosen for optimum signal-to-noise ratio. Measurements by Putley[9] of a similar germanium bolometer supplied by the author gave a responsivity $R \approx 10^3$ V/W

and relaxation times obtained from d.c. resistivity and Hall effect measurements[8]. Some uncertainty is introduced in our calculation because hopping of carriers between impurity sites is the dominant conduction process in germanium bolometers, so relaxation times may be frequency-dependent. Assuming, however, that the lattice does dominate the reflectivity of both bolometers, we expect the germanium to reflect a constant 36 per cent from 5 to 100 cm^{-1} and the carbon to reflect a constant 25 per cent, just as it does at 20 and 77°K. The somewhat surprising roll-off in measured relative responsivity of the carbon bolometer at high frequencies may be attributable to an excess of soot in the light pipe and cavity used for mounting it.

INDIUM ANTIMONIDE DETECTOR

A third type of detector useful in the 10–100 cm^{-1} region is the indium antimonide detector developed by Putley and others. For a review of the properties of the detector which is sometimes called a photoconductor or an electronic bolometer, see Putley[10]. The reason for the confusion in nomenclature is that under typical operating conditions the various parameters which describe the behaviour of the charge carriers, such as the plasma frequency, the cyclotron frequency, the conductivity relaxation frequency, the impurity depth, and the photon energy are all the same order of magnitude. Therefore, few of the usual simplifying assumptions can be made in the theoretical description of the detector.

It is helpful to think of the indium antimonide detector as an electronic bolometer. Because of a relatively long electron-lattice relaxation time the electrons are the active element and the lattice, which is cooled by immersion in liquid helium acts as a thermal bath. Because of the low specific heat of the carriers, this type of bolometer is very fast. 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 neighbourhood 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 centres 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 centres contract and separate impurity levels develop. At low temperatures, therefore, a magnetic "freeze-out" of carriers occurs causing the large resistivity illustrated in *Figure 4*.

The representative indium antimonide detector shown in *Figure 2* is a $1{\cdot}8 \times 3 \times 5$ mm block of *n*-type indium antimonide with a carrier density of $\approx 10^{14}/\text{cm}^3$. It was supplied to the author by Putley for the purpose of comparative detector tests. The leads are attached with indium solder and it was mounted in a niobium zirconide superconducting solenoid as shown in *Figure 1*. Measurements of the responsivity of this detector relative to the indium doped germanium bolometer are shown in *Figures 3* and *4*. 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. 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 l associated with the first ($n = 0$) and second ($n = 1$) Landau levels. The lower energy peak can be identified as $l = 1$, $n = 0$ to $l = 1$, $n = 1$ and the higher as $l = 0$, $n = 0$ to $l = 0$, $n = 1$[11].

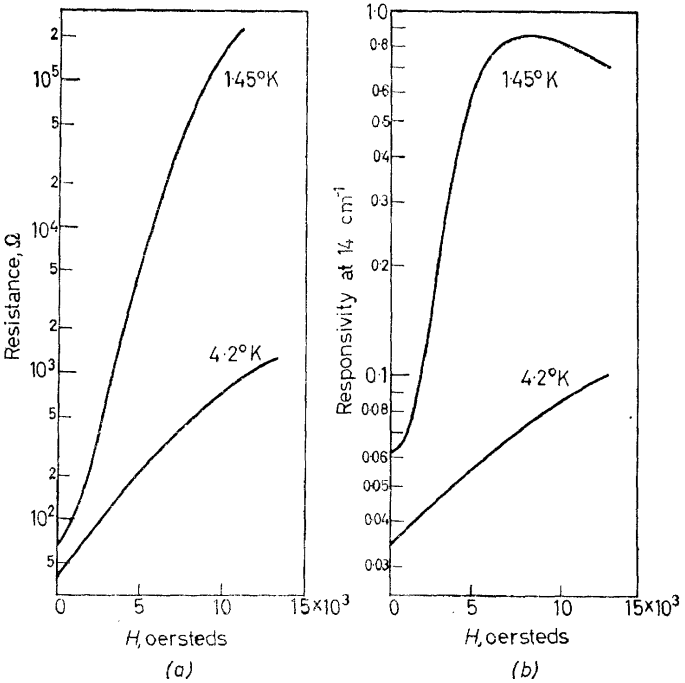


Figure 4. Magnetic field dependence of the impedance and responsivity of the indium antimonide detector. Bias current was set for optimum signal-to-noise ratio

The responsivity of the indium antimonide detector increased with bias current up to the onset of avalanche breakdown. At higher currents the detector noise becomes much larger than amplifier noise. Responsivity and resistance measurements were made at the current for optimum signal-to-noise ratio.

AMPLIFIER NOISE

Since the indium antimonide and the germanium bolometer are limited by amplifier noise, it is not possible to assign a meaningful figure of merit such as a detectivity or D^* to the detector itself. The nature of the amplifier used must be considered. For the relatively slow bolometers, an amplifier with a high impedance input and a good low frequency noise figure was required†. For the indium antimonide detector, which was operated at 1 kHz, several lower input impedances were desirable and low frequency noise was not important‡. Using our amplifiers, the optimum performance of the indium antimonide detector occurred at $H = 4{\cdot}4 \times 10^3$ oersteds, where its noise equivalent power (NEP) at 10 cm^{-1} was about one third that of the germanium bolometer. The carbon bolometer, which was current noise limited, had an NEP 20 times that of the germanium bolometer.

Our observation of optimum performance for the indium antimonide detector at $H = 4{\cdot}4 \times 10^3$ oersteds was a consequence of the good noise figure of our amplifier at a load impedance of 4 kΩ§. Given an ideal transformer, this noise figure could be maintained at much lower load impedances. *Figure 4* shows that the square of the voltage responsivity of the indium antimonide detector falls less rapidly than its resistance§ as H is decreased. Therefore, given an *ideal* noise-free transformer, optimum performance would occur at $H = 0$. Rollin[14,15] has reported excellent results operating in this way using a transformer wound with superconducting wire. 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 antimodide samples[10].

CONCLUSION

The difference between the NEP values measured from our germanium bolometer and indium antimonide detector, is comparable to the variations expected between different samples. The choice between them, at least in their present stage of development, must therefore depend on other factors. If speed is required, the indium antimonide detector is clearly indicated. Also, its irregular frequency response might help to solve the filtering problems associated with order separation in grating spectrometers. This is particularly true at frequencies above $\sim$50 cm^{-1} if the magnetic field is controlled so that the cyclotron resonance frequency coincides with the desired grating order[16]. Its sensitivity to magnetic field and the requirement of either a field or a superconducting transformer can cause difficulties when large fields are required elsewhere in the experiment. The germanium bolometer is insensitive to magnetic fields and its relatively flat frequency response is useful with Fourier transform spectroscopy where large regions of the spectrum are studied at one time. Its requirements of vacuum, and pumped helium temperatures can, however, complicate cryogenic systems. Because the author has not used carbon bolometers consistently in recent years, the one tested here may not be representative of the best available performance. In past years, comparisons have shown a somewhat

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† George Associates lock-in amplifier with three-stage nuvistor preamplifier. Noise characteristics are similar to those advertised for the Princeton Applied Research HR-8 with Type A preamplifier. See reference 12.

‡ Princeton Applied Research JB-5 lock-in amplifier with CR-4 preamplifier. For noise characteristics see reference 13.

§ More precisely, it is the differential detector resistance $\mathrm{d}V/\mathrm{d}I$, not $R = V/I$, which is important for matching to the amplifier. In the operating range $\mathrm{d}V/\mathrm{d}I \approx R/2$ for the indium antimonide detector.

larger responsivity from carbon bolometers than from doped germanium bolometers, and a NEP which is larger by only a factor of three to four. It seems clear, however, that the NEP for the carbon resistance bolometer is sufficiently larger than that for the other detectors that it cannot be recommended for any application in the far infrared except, perhaps, as a first exercise in building a helium temperature bolometer.

I have used doped germanium bolometer detectors for far infrared Fourier transform spectroscopy of solids with considerable success. The spectroscopic techniques[6] and the specialized cryogenic systems[17], developed for measuring the optical properties of solids as a function of temperature and magnetic field have been fully described elsewhere.

A wide range of problems have been studied using this apparatus. These include ferromagnetic, anti-ferromagnetic and exchange resonances in ordered magnetic insulators[17,18] electron spin resonance and spin-orbit combination resonance in bismuth[19] and spectra of gas molecules trapped in the β-quinol clathrates[20].

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