Agreement between theory and experiment is good; the parameters that best fit the data indicate that nearly all the traps are initially filled. Further theoretical studies are needed to elucidate the connection between the macroscopic phenomenological parameters (17) and microscopic interactions responsible for trapping and photoexcitation. However, it may be stated quite firmly that the second-order excitation process, Eq. (16), is correct; attempts to fit the data with linear or cubed intensity dependence were unsuccessful.

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¹N.J. Berg, B.J. Udelson, and J.N. Lee, *Appl. Phys. Lett.* **31**, 555 (1977).

²F.S. Chen, *J. Appl. Phys.* **38**, 3418 (1967).

³W.D. Johnston, Jr., *J. Appl. Phys.* **41**, 3279 (1970).

⁴J.J. Amodi, *RCA Rev.* **32**, 185 (1971).

⁵D. von der Linde, A.M. Glass, and K.F. Rodgers, *Appl. Phys. Lett.* **25**, 155 (1974).

⁶We assume the spatial variation of the acoustic-wave field to be sufficiently slow so that the electric current due to diffusion processes is negligible compared to that due to conduction, as given by Eq. (2).

Microbolometers for infrared detection

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We describe a novel room-temperature detector for the wavelength range 10–1000 μm . This detector consists of a thin bismuth bolometer film with dimensions much smaller than a wavelength. The small size of the detector results in reduced NEP and faster response. A video NEP of $1.6 \times 10^{-10} \text{ W/Hz}^{1/2}$ is obtained at 119 μm , remaining within a factor of 10 of this value for modulation frequencies up to 25 MHz. When used as a mixer, the device is predicted to have an NEP of $3.5 \times 10^{-18} \text{ W/Hz}$. It is easily fabricated with conventional planar processing techniques and can be replicated in arrays. The device is expected to be most useful when the radiation to be detected is spatially coherent.

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A most convenient and generally useful infrared detector would have the following properties: low NEP, fast response, wide spectral range, room-temperature operation, and ease of fabrication. In the spectral range 10–1000 μm no detector possessing all these attributes is presently available, and the choice of a detector depends on the primary needs of the particular application. In this letter we describe a novel microbolometer detector, distinguished from conventional bolometers by the fact that the temperature-sensitive element is much less than a wavelength in size. Among room-temperature FIR detectors the microbolometer offers an advantageous combination of low NEP and speed, has wide spectral range, and is easy to fabricate.

The microbolometer consists of a thin bismuth film, the resistance of which varies with temperature. Thin-film bismuth bolometers with larger area have been studied by Contreras and Gaddy¹ and Block and Gaddy,² who showed that response times in the nanosecond range could be obtained through the use of substrates with high thermal conductivity. However, while the use of such a substrate increases the bandwidth of the device, the responsivity is reduced and NEP increases. Schwarz and Ulrich³ suggested that bolometers could also be improved by making them smaller than the wavelength to be received. In this case an antenna must be used to capture radiation which would otherwise bypass the small detector.

This approach seems intuitively to be advantageous because it makes a comparatively large amount of energy available to heat a very small bolometer, resulting in larger temperature changes. The analysis of Ref. 3 is inadequate for the present case, however, because it assumed the thermal conductance between the bolometer and its environment to be independent of modulation frequency and proportional to the area of the bolometer. When we take into account the correct dependence of thermal conductance on bolometer size and modulation frequency, we find that not only is NEP improved by reducing bolometer size, but a large increase in bandwidth is obtained as well.

Let us assume that the bolometer lies on the surface of a substrate. When radiation is applied, the temperature of the bolometer increases from T_0 to $T_0 + \Delta T$. If the incoming radiation is modulated at the frequency f , the heat balance equation is

$$2\pi f C \Delta T + G(f) \Delta T = W, \quad (1)$$

where C is the thermal capacity of the bolometer, $G(f)$ is the thermal conductance between the bolometer and its environment, and W is the Fourier component at frequency f of the input radiation power. The signal voltage obtained from the device is $v = \alpha V_B \Delta T$, where α is the temperature coefficient of resistivity, defined by $\alpha = \rho^{-1}(d\rho/dT)$, and V_B is the dc

bias voltage. Thus, the signal voltage is

$$v = \frac{\alpha V_B W}{G(f) + 2\pi j f C} \quad (2)$$

The thermal conductance G is equal to $G_S + G_A + G_M$, where G_S is the component arising from conduction to the substrate, G_A to the air, and G_M to the metal contacts. G_A can be neglected in comparison with the other components because air is a poor conductor of heat. Conduction of heat through the substrate is given by

$$G_S(f) = K_S(\Delta T)^{-1} \int \nabla T \cdot dS, \quad (3)$$

where K_S is the thermal conductivity of the substrate, T is the temperature of the substrate, and the integral is over the contact between the bolometer and the substrate. The temperature of the substrate is governed by the diffusion equation

$$K_S \nabla^2 T - 2\pi j f H_S T = 0, \quad (4)$$

where H_S is the substrate heat capacity. For convenience we shall model the bolometer-substrate contact as a hemisphere of radius a ; the area of the hemisphere $2\pi a^2$ is set equal to A , the actual area of the contact. In the limit of small f the temperature of the substrate obeys Laplace's equation, and $T = T_0 + \Delta T(a/r)$. Hence, from Eq. (3), $G_S(0) = 2\pi a K_S$. As f increases, heat flow is still radial, but $T = T_0 + \Delta T(a/r) \exp[-(r-a)/L_S]$, where $L_S = (K_S/2\pi j f H_S)^{1/2}$ is a complex heat diffusion length. As long as $|L_S| \gg a$ (that is, as long as $f \ll f_1$, where $f_1 = K_S/2\pi a^2 H_S$), the new exponential factor has little effect on ∇T near $r = a$, and the approximation $G_S \approx 2\pi a K_S$ (independent of f) remains valid. For $f \gg f_1$, however, the exponential term is important, and $|\nabla T| \approx \Delta T/L_S$ at $r = a$. Thus, for $f \gg f_1$, $G \approx 2\pi a^2 K_S/L_S$, which varies as $f^{1/2}$. The additional component of the total heat conductance arising from the electrical contacts is difficult to calculate precisely. Because of the larger thermal conductivity of the metal, the magnitude of the heat diffusion length in the metal, L_M , is much larger than that of L_S . Thus, an upper limit on $|G_M|$ is $K_M A'/|L_S|$, where K_M is the thermal conductivity of the metal and A' is the cross-sectional area of metal contacts. We find that $K_M A'/|L_S|$ is about 60% of $|G_S|$, and inasmuch as this represents an upper limit for $|G_M|$ we assume an intermediate value for G_M and set $G = 1.3G_S$. We note that inasmuch as $|G_M| < |G_S|$, the final results will not depend strongly on this approximation.

Having now found $G(f)$, the responsivity of the bolometer can be found from Eq. (2). We note that there are three frequency ranges of interest. For $f \ll f_1$, responsivity is independent of frequency. When f becomes larger than f_1 , G increases as $f^{1/2}$ and responsivity decreases as $f^{-1/2}$. At a higher frequency, $f_2 = (1.3)^2 2\pi a^4 K_S H_S / C^2$ (note $f_2 > f_1$ as long as the thickness of bolometer is less than a), the second term in the denominator of Eq. (2) begins to dominate. Thus, for $f \gg f_2$ responsivity varies as f^{-1} . In our devices the usable bandwidth of the device depends on f_1 and thus is proportional to A^{-1} .

The structure of our experimental device is shown in Fig. 1. Bismuth is used because of its relatively large α (mea-

sured for our films to be 3.3×10^{-3}) as well as its high resistivity, which is desirable to facilitate impedance matching to the antenna. The antenna and the procedure for fabrication have been described elsewhere.⁴ The bismuth bolometer element, 55 nm thick, is deposited across the terminals of the antenna. The dimensions of the bolometer, excluding the portion overlapping the antenna, are about 5 by 4 μm , resulting in a dc resistance of 170 Ω . A quartz superstrate is required over the device to allow correct operation of the antenna, as explained in Ref. 4. However, because the antenna is thicker than the bolometer, there is a small air space, about 0.1 μm wide, separating the bolometer from the superstrate; this reduces heat conduction through the superstrate to less than 5% of the total, which can be neglected. Both substrate and superstrate are crystal quartz, with the optic axis parallel to the surface and parallel to the axis of the antenna. (Crystal quartz is used because it is transparent at the experimental wavelength of 119 μm .) Values of H_S and K_S for quartz are taken from the literature.^{5,6} Signal voltage is proportional to dc bias voltage, but bias voltages greater than about 0.5 V were found to damage the Bi film; in the experiments being described a bias of 0.5 V was used. The noise of the detector was measured from 250 Hz up to 10 kHz using a PAR 124A lock-in amplifier and was found to be close to the Johnson noise of its resistance R_0 , even when the largest practicable bias current is flowing.

Using the approximate method outlined above for the calculation of $G(f)$, the voltage responsivity $R \equiv v/W$ of the detector can be predicted from Eq. (2). Its noise equivalent power for unit bandwidth can then be predicted using $\text{NEP} = (4kTR_0)^{1/2}/R$. This result is shown as curve A in Fig. 2. This prediction neglects noise introduced by the amplifier which follows the detector as well as the inevitable rolloff of responsivity at higher frequencies due to the amplifier's input capacitance. The importance of both effects is

FIG. 1. (a) Sketch of bolometer and antenna. (b) Magnified view of microbolometer.

FIG. 2. Curve A: predicted NEP of microbolometer for unit bandwidth versus modulation frequency. 0.5-V dc bias is assumed. Circles are experimental points. Curve B: experimental curve for commercial pyroelectric detector, 1 mm in diameter. The solid portion of the curve is the manufacturer's published specification; the dashed continuation is our own extrapolation.

reduced by the conveniently low impedance of the detector. The frequency at which amplifier capacitance becomes important will depend on the details of the amplifier and coupling network but will in most cases be above the useful frequency range of the detector as determined by its thermal properties. For comparison, several experimental points are also shown in Fig. 2. These points result from measurements of voltage responsivity at several frequencies, from which NEP is then calculated using $\text{NEP} = (4kTR_0)^{1/2}/R$. For $f < 10$ kHz, responsivity is measured with a mechanically chopped CH_3OH laser, the intensity I of which is measured independently with a pyroelectric detector. The power W applied to the bolometer is calculated from $W = I\sigma\eta$, where σ is the antenna effective area⁷ equal to $\lambda^2 g/4\pi$, η is an efficiency factor which may be less than unity because of impedance mismatch between the antenna and the bolometer, and g is the antenna gain. In earlier work⁴ the gain has been estimated from electromagnetic theory to be 5.7, and the experimental points in Fig. 2 are therefore plotted under the assumptions $g = 5.7$ and $\eta = 1$. Measurements of responsivity were also made at 10, 20, and 30 MHz. Since no means of modulating the 119- μm laser at such high frequencies was available, these measurements were made by beating two 10.6- μm CO_2 lasers. (It was necessary to change to a CaF_2 substrate for this part of the experiment because quartz is absorptive at 10.6 μm . The thermal constants of CaF_2 are known^{8,9} and the appropriate corrections were applied.) The responsivity at these frequencies relative to that at audio frequencies was then obtained by comparing the beat signal from the bolometer with the audio signal obtained from a mechanically chopped CO_2 laser. The resulting data points are also shown in Fig. 2. Comparing the experimental points with the theoretical curve we see that the variation of NEP with modulation frequency is in good agreement with theory. The experimental points systematically lie slightly below the theoretical curve; this is probably due to small errors in the values assumed for K_S , H_S , G_M , g , and α .

We see that the NEP of the microbolometer at low modulation frequencies is about $1.6 \times 10^{-10} \text{ W/Hz}^{1/2}$, and

remains within a factor of 10 of this value for modulation frequencies up to 25 MHz. For comparison, curve B in Fig 2 shows a similar NEP curve for a commercially available pyroelectric detector with an FET amplifier. (Because the responsivity of the high-impedance pyroelectric detector is strongly affected by capacitance even at relatively low frequencies, it is most reasonable to consider the detector and amplifier as a unit.) It should be noted that the pyroelectric detector is 1 mm in diameter. At frequencies above 1 kHz, the NEP of the pyroelectric detector increases strongly with frequency as a result of its capacitance and very high source resistance. The microbolometer, with its lower resistance, does not experience rolloff from this cause until a much higher frequency. Below about 300 MHz its NEP increases only as the square root of frequency, so that it is much less than the pyroelectric detector's NEP in this frequency range.

The microbolometer might also be useful as a mixer in receivers requiring low NEP, room-temperature operation and modest bandwidth. We have estimated the NEP of our microbolometer in this role under the assumption of 3.8 mW local oscillator power as shown in Fig. 3. (Oscillator power is limited by the temperature rise of the bismuth element; 3.8 mW results in 25 °C.) The low NEP (less than 10^{-17} W/Hz below 125 kHz) and low local oscillator power requirement should be useful, but the available bandwidth is quite small compared with most heterodyne receivers.

The devices described here have not been optimized, and it seems probable that better performance can be gained through technical improvements. For example, if the bismuth film could be made to withstand larger bias currents, NEP would decrease in direct proportion. The devices are quite easy to fabricate and lend themselves well to replication in arrays. They are expected to work well throughout the wavelength range 10 μm –1 mm, with the best performance probably available at the longer wavelengths where high-gain antennas become easier to fabricate. It should be noted that in order to utilize the low NEP it is necessary to capture radiation with a primary mirror or lens, just as a microwave "dish" captures radiation and couples it to a

FIG. 3. Estimated NEP of microbolometer (1-Hz bandwidth), when used as a mixer, versus beat frequency. LO power of 3.8 mW and dc bias of 0.5 V are assumed.

waveguide horn. This can be done efficiently if the incoming radiation is a plane wave or Gaussian beam, but the process will be inefficient if the incoming wave fronts are heavily distorted or if the radiation is derived from a nearby spatially extended noise source. Thus, the device seems most likely to be useful in communications or astronomical applications, and especially in those cases where atmospheric distortion of wave fronts is not pronounced.

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¹B. Contreras and O.L. Gaddy, Appl. Phys. Lett. **18**, 277 (1971).

²W.H. Block and O.L. Gaddy, IEEE J. Quantum Electron. **QE-9**, 1044 (1973).

³S.E. Schwarz and B.T. Ulrich, J. Appl. Phys. **48**, 1870 (1977).

⁴T.-L. Hwang, D.B. Rutledge, and S.E. Schwarz, Appl. Phys. Lett. **34**, 9 (1979).

⁵*American Institute of Physics Handbook*, 3rd ed. (McGraw-Hill, New York, 1972), p. 4-158. Thermal conductivity of crystal quartz parallel to the optic axis is different from that perpendicular to the optic axis. At frequencies where $|L_S| \gtrsim a$ we used the average thermal conductivity, while at higher frequencies we used K_{S1} .

⁶Landolt-Bornstein, *Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik, und Technik* (Springer-Verlag, Berlin, 1961), II. Band, 4. Teil, p. 195.

⁷S. Ramo, J.R. Whinnery, and T. Van Duzer, *Field and Waves in Communication Electronics* (Wiley, New York, 1965), p. 717.

⁸Reference 5, p. 4-157.

⁹Reference 6, p. 211.