and a conversion efficiency slightly less than 0.1, which should represent a very useful device in this frequency range.

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Material Characterization and Ultimate Performance Calculations of Compensated n-Type Silicon Bolometer Detectors at Liquid-Helium Temperatures

C. J. SUMMERS AND S. ZWERDLING

***Abstract*—The dependence of the resistivity and far infrared (FIR) absorptance on donor concentration, compensation, and temperature in compensated n-type Si is reported. The effect of environment, time constant, and spectral passband on the noise equivalent power (NEP) of the compensated Si bolometer is examined and compared with similar calculations for the compensated Ge bolometer.**

INTRODUCTION

THE important characteristics required for a semiconductor bolometer element with a low-noise equivalent power (NEP) are: 1) a high value for the temperature coefficient of resistance α_R, 2) a value of resistance R compatible with a low-noise preamplifier, 3) a high absorptance A_t, and 4) a low value for the thermal capacitance $\mathcal{C}$. Suitably doped Ge crystals partially fulfill all these requirements. However, the smaller thermal capacitance of Si and the larger temperature dependence of the resistivity reported for properly doped crystals indicate that Si may be superior to Ge as the impurity-host crystal for a far infrared (FIR) bolometer element. This paper reports on an investigation of this possibility and on the doping levels in Si which lead to optimum detector performance. The first requirement is best satisfied by a Si crystal having a small donor concentration N_D and a low compensation ratio K_n, whereas satisfying the second and third requirements necessitates a large N_D value and a reasonably large value of K_n. A series of samples with N_D in the range 0.5–2 $\times$ 10^{18}/cm^3 and K_n between 0.05–0.4 was therefore prepared and characterized to determine those electrical and optical properties from which their performance as bolometer elements can be calculated.

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MATERIAL CHARACTERIZATION

Measurements to determine the dependence of the resistivity ρ on temperature T have been performed between 1.5–4.2 K and the data fitted to the expression $\rho = \rho_0 \exp(AT^{-n})$ using a least squares regression. The parameter ρ_0 is a constant and the quantity A is related to α_R through the expression: $\alpha_R = 1/R(dR/dT) = -nAT^{-(n+1)}$. Two recent theories of hopping conduction [1], [2] have concluded that ln ρ should have a $T^{-1/4}$ or

$T^{-1/2}$ rather than a T^{-1} dependence, as given by a previous theory [3]. The data were therefore fitted using $n = 0.25$, 0.5, and 1.0, and for all samples the value $n = 0.5$ (also 0.25) gave a considerably better fit than $n = 1.0$. The data are plotted in Fig. 1, which shows that for samples with the same compensation ratio ($K_n = 0.1$ and 0.4), increasing the value of N_D causes a very large decrease in the resistivity, whereas the temperature dependence as given by the slope of the lines is only slightly affected. For samples in which N_D is nearly the same (i.e., $N_D = 8.9 \times 10^{17}/\text{cm}^3$, $1.0 \times 10^{18}/\text{cm}^3$, and $1.3 \times 10^{18}/\text{cm}^3$), increasing K_n results in a large decrease in resistivity, but again the slope A is only slightly affected, having the value $26.3(K^{1/2})$ for the top line and $18.6(K^{1/2})$ for the bottom line. These results indicate that the resistance of a bolometer element can be adjusted over a broad range by impurity doping to the best possible value with little effect on α_R.

FIR measurements with specimens at 4.2 K have also been made between 40–1000 μm to determine the wavelength dependence of the absorption coefficient α, the single-surface reflectance R_1, and the dependence of these parameters on N_D and K_n. From these data, the total absorptance of the element A_t was obtained from the expression [4], [5]

$$A_t = \frac{(1 - R_1)[1 - \exp(-\alpha d)]}{[1 - R_1 \exp(-\alpha d)]}$$

where d is the thickness of the specimen. The value of R_1 obtained for the Si specimens was 29.5 percent, indicating that for a single external incidence of radiation on a bolometer element, the maximum possible value of A_t is 70.5 percent. The results obtained for the specimen with $N_D = 2.0 \times 10^{18}/\text{cm}^3$, $K_n = 0.1$, and $d = 0.25$ mm showed that for this thickness, A_t reaches the maximum value of 70.5 percent in the range 40–166 μm. The specimen with $N_D = 1.3 \times 10^{18}/\text{cm}^3$ and $d = 0.25$ mm but with $K_n = 0.4$, however, showed an average value of A_t of about 16 percent with some spectral dependence. By enclosing either of these materials in a cryogenically cooled integrating sphere, the effective total absorptance is expected to be increased considerably. These two samples also have the lowest resistivity and are therefore good candidate materials from which to make bolometer elements.

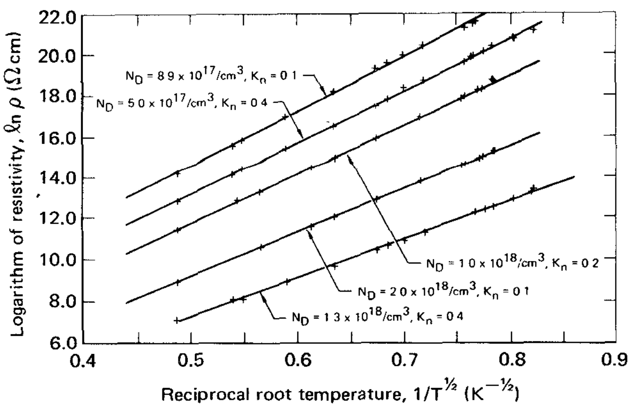

Fig. 1. Temperature dependence of resistivity for hopping conduction in n-type compensated silicon containing arsenic donor concentrations N_D and boron acceptor concentrations N_A. The donor concentrations and the compensation ratios $K_n = N_A/N_D$ are indicated.

BOLOMETER PERFORMANCE CALCULATIONS

The resistivity values and the known thermal properties of Si were substituted into the relationship [5] for the responsivity $\mathcal{R}$ and for the noise power originating from various sources. The NEP values of bolometer elements obtainable from each crystal were then calculated from these values. The calculations were arranged to give the optimum performance for a detector operating in an optical system in which the f-number spectral passband (as controlled by liquid-helium cooled filters) and thermal time constant τ_{th} were specified and only the detector size and reservoir temperature T_0 could be varied. The thermal time constant is equal to the ratio of the thermal capacitance $\mathcal{C}$ to the dynamic thermal conductance of the bolometer and its leads $\mathcal{G}_d$, that is, $\tau_{th} = \mathcal{C}/\mathcal{G}_d$. Full account was taken of the effect on both the responsivity and noise of the absorbed blackbody radiant power lying within the spectral passband and originating from a 296-K background.

With these input parameters, the procedure described by Low [6] was used to determine the optimum temperature of the element T and hence the bias voltage which maximizes the responsivity. The temperature, resistance, responsivity, noise, and resultant NEP values were then calculated as a function of the spectral passband as defined by the shorter cut-on wavelength λ_{on} and the longer cutoff wavelength λ_{off}. The results for a bolometer element obtained from one of the most suitable materials and designed to have $\tau_{th} = 10$ ms are shown in Figs. 2 and 3 as a function of λ_{on} with $\lambda_{off} = 3000$ μm, for an optical system in which the f number equals 2. A detector size of 2×2 mm by 0.25 mm thick was assumed, and the calculations were performed for reservoir temperatures of 1.5 and 4.2 K.

As shown in Fig. 2, the temperature of the element increases as λ_{on} decreases to 10 μm and more of the integrated blackbody radiant power from the 296-K background is incident on the detector. In this circumstance, the thermal capacitance of the element, which is proportional to T^3, increases rapidly, and a corresponding increase in the value used for the thermal conductance of the bolometer leads must be made to keep $\tau_{th} = 10$ ms. The curves of Fig. 2 show that for $T_0 = 1.5$ K, the overall consequence is a decrease in the responsivity by three orders of magnitude as the spectral passband is thus increased. However, a similar decrease occurs in R, which is very helpful for achieving optimum source impedance for low-noise-figure performance with available preamplifiers.

For a reservoir temperature of 4.2 K, Fig. 2 shows that

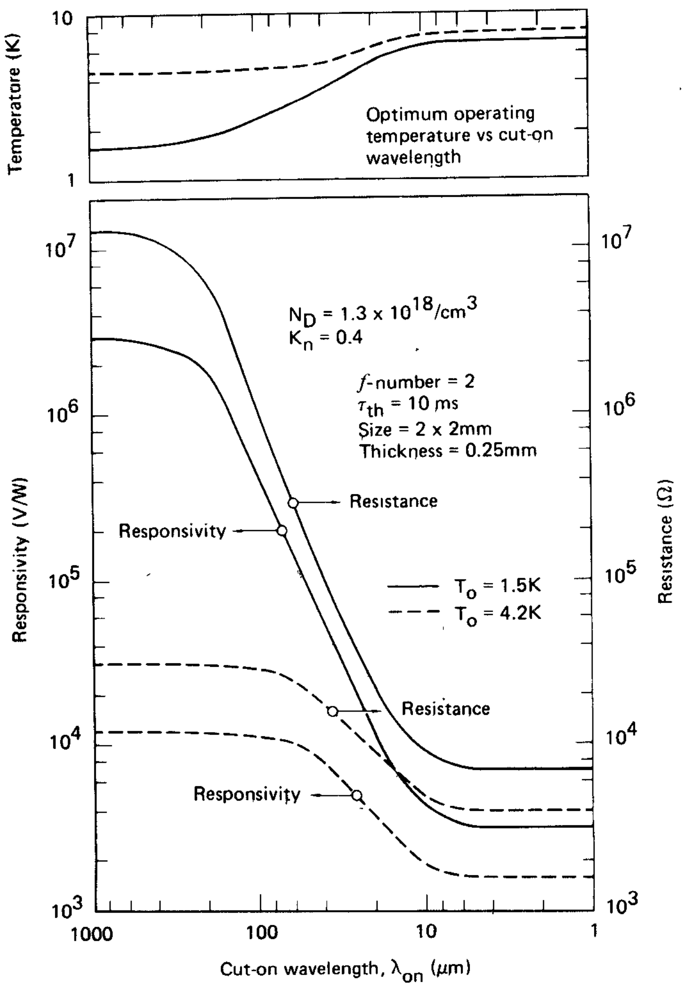

Fig. 2. Temperature, responsivity, and resistance as a function of λ_{on} for a silicon bolometer element with $N_D = 1.3 \times 10^{18}/\text{cm}^3$, $K_n = 0.40$, and $T_0 = 1.5$ and 4.2 K. These values were calculated for the following parameters: f number $= 2$, $\tau_{th} = 10$ ms, $\lambda_{off} = 3000\ \mu$m, $A_t = 0.5$, detector size 2×2 mm by 0.25 mm thick.

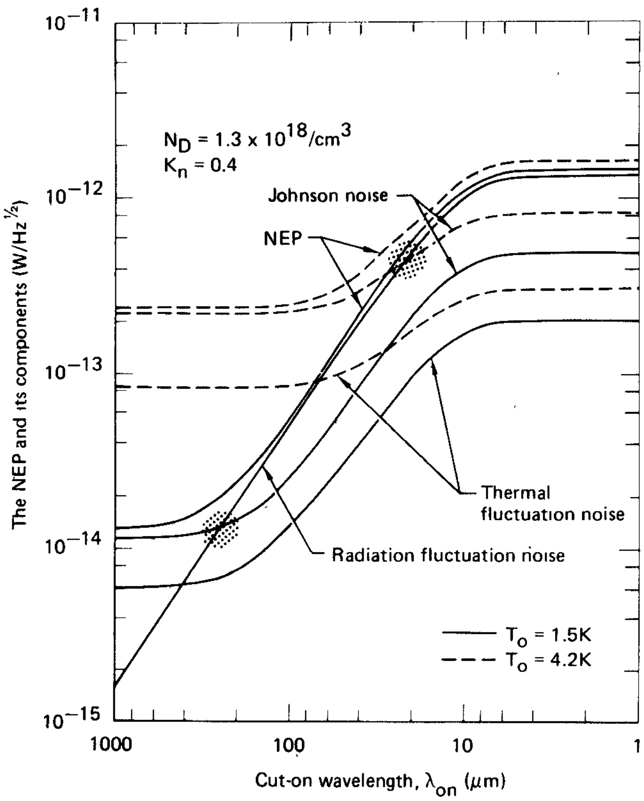

Fig. 3. The NEP and the Johnson, thermal fluctuation, and radiation noise terms as a function of λ_{on} for a silicon bolometer element with $N_D = 1.3 \times 10^{18}/\text{cm}^3$ and $K_n = 0.40$. These values were calculated for the same parameters listed in the caption for Fig. 2.

much lower responsivity values are obtained for cut-on wavelengths greater than 30 μm than when $T_0 = 1.5$ K. The lower values of $\mathcal{R}$ are mainly a result of the increase in the thermal capacitance of the element but also because of the $T^{-3/2}$ temperature dependence of α_R and the drop in the bias voltage resulting from the lower resistance of the element. Furthermore, Fig. 2 shows that as the cut-on wavelength decreases, the bolometer temperature increases and the responsivity and resistance decrease, but not as rapidly or by as much as for the lower reservoir temperature. This is because for the same thermal time constant of 10 ms, the value of $\mathcal{G}_d$ is larger (since $\mathcal{C}$ is larger), and therefore the rate of heat removal from the bolometer element is greater. Thus the temperature difference between the bolometer element and the cryogenic reservoir $(T - T_0)$ is smaller and the changes in $\mathcal{R}$, R, and $\mathcal{G}_d$ with λ_{on} are less than for $T_0 = 1.5$ K.

The NEP and the contributions to the NEP from: 1) the Johnson noise term, defined as $V_J/\mathcal{R}$ where $V_J = (4kTR)^{1/2}$ is the Johnson noise voltage, 2) the thermal fluctuation noise power W_T given by $W_T = (4kT^2\mathcal{G}_d)^{1/2}$, and 3) the radiation fluctuation noise power W_R are related by the expression

$$\text{NEP} = \left[\frac{V_J^2}{\mathcal{R}^2} + W_T^2 + W_R^2\right]^{1/2}$$

$$= \left[\frac{4kTR}{\mathcal{R}^2} + 4kT^2\mathcal{G}_d + W_R^2\right]^{1/2} \qquad (1)$$

where k is Boltzmann's constant.

Fig. 3 shows a plot of the NEP and its principal components as a function of the cut-on wavelength, calculated for the same bolometer element and system parameters as used in Fig. 2. Before discussing the NEP, it is informative to consider the behavior of the noise sources separately. The radiation noise term increases (almost linearly on this logarithmic plot) until just below a cut-on wavelength of 10 μm at which point essentially all of the blackbody energy of the 296-K background has been included in the spectral passband admitted to the detector. This noise component is, of course, independent of the reservoir temperature, since $T \ll 296$ K [7].

The thermal-fluctuation noise term remains fairly constant for cut-on wavlengths between 1000–200 μm, but then begins to increase rapidly up to 10 μm, below which it becomes constant. This behavior is a consequence of the heating of the bolometer by the increased background radiation, resulting in a temperature rise of the element and a necessarily larger value for $\mathcal{G}_d$ in order to maintain τ_{th} at 10 ms, both of which cause an increase in W_T.

The Johnson noise term has a similar dependence on cut-on wavelength and increases as λ_{on} decreases toward 10 μm, because its inverse dependence on $\mathcal{R}$ dominates its dependence on $R^{1/2}$.

From the curves in Fig. 3 for $T_0 = 1.5$ K, the NEP is limited by the Johnson noise term for cut-on wavelengths greater than 220 μm, above which it has a value less than 1.5×10^{-14}-W/Hz$^{1/2}$. For cut-on wavelengths less than 220 μm the bolometer is limited by background-radiation fluctuation noise.

For $T_0 = 4.2$ K, the performance of the bolometer is limited by the Johnson noise term for cut-on wavelengths greater than 25 μm. The Johnson noise term increases as a direct consequence of the large decrease in the responsivity that occurs when T_0 is raised from 1.5 to 4.2 K (Fig. 3) and which dominates the effect that a lower resistance has on the Johnson noise voltage, as discussed earlier. The result of all these changes is an increase in the FIR value of the NEP by a factor of about 20 above that obtained at 1.5 K. As the cut-on wavelength decreases toward 10 μm, the 4.2-K NEP performance is degraded in a similar manner to that found for $T_0 = 1.5$ K. However, the dependence on cut-on wavelength is less, because the dependence of $\mathcal{R}$ on λ_{on} at 4.2 K is less, as shown in Fig. 2.

To improve upon these calculated values for the NEP, the noise term which limits the performance must first be ascertained. For a background-limited detector, the NEP can be decreased by increasing the f number or decreasing the size of the element. If the NEP is limited by the Johnson noise term, a lower NEP can be obtained by decreasing the element size, altering its geometry, or most effectively, by lowering T_0. Further benefits can only come from an improvement of the detector material so as to yield a higher value of α_R and/or a lower resistance, thereby reducing the magnitude of $V_J/\mathcal{R}$. However, any change in the magnitude of the radiation signal reaching the bolometer element, which might arise from a geometrical change in either the optical detector system or the detector element, must be considered when the NEP of the modified system is calculated and compared with the above values.

The curves in Fig. 4 show the effect of the thermal time constant on the NEP for $T_0 = 4.2$ and 1.5 K. As τ_{th} is decreased from 10 ms, first to 1 ms and then to 0.1 ms, the long-wavelength performance is degraded, i.e., for $T_0 = 1.5$ K, the NEP increases from 1.5×10^{-14} to 4×10^{-14} and then to 1.3×10^{-13} W/Hz$^{1/2}$, respectively. This degradation in performance is found to be a direct result of lower values for the responsivity.

For the same element size and operating conditions, the thermal time constant of a bolometer can only be decreased by increasing $\mathcal{G}_d$. When this is done, it is found that to achieve approximately the same value of $(T - T_0)$ which

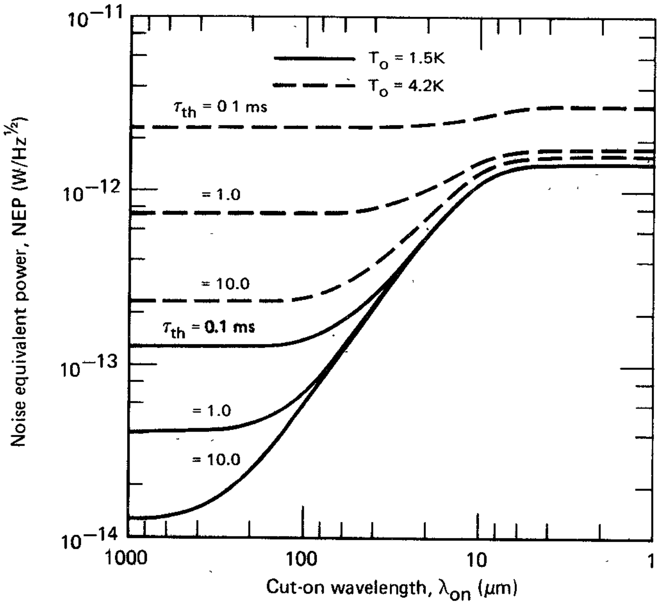

Fig. 4. The NEP as a function of λ_{on} for a silicon bolometer element with $N_D = 1.3 \times 10^{18}$/cm^3 and $K_n = 0.4$ for different values of T_0 and τ_{th}. These NEP values were calculated for the same parameters listed in the caption for Fig. 2.

maximizes the responsivity, an increase in the electrical power dissipated in the bolometer, and hence in the bias voltage, is required. Analysis of the consequences of these changes shows that the responsivity is approximately proportional to $\tau_{th}^{1/2}$. At long wavelengths, the Johnson noise dominates the other noise contributions and is found to be only slightly affected by changes in τ_{th}. In this situation, the NEP $\approx V_J/\mathcal{R}$, and therefore is inversely proportional to $\tau_{th}^{1/2}$. This conclusion is confirmed by the long-wavelength results for the NEP shown in Fig. 4.

For the optical system assumed in these calculations and for $T_0 = 1.5$ K, the radiation fluctuation noise dominates for cut-on wavelengths less than 220 μm when $\tau_{th} = 10$ ms, and for cut-on wavelengths less than 40 μm when $\tau_{th} = 0.1$ ms. As a result, the curves converge as λ_{on} approaches 40 μm, below which the NEP becomes independent of τ_{th}.

The results obtained for $T_0 = 4.2$ K behave similarly. Below a value of $\tau_{th} = 0.1$ ms, the dependence of the NEP on the cut-on wavelength becomes small, a characteristic which arises when the electrical power dissipated in the element is much greater than the absorbed background radiant power. Fig. 4 also shows that the very large improvement in the FIR NEP performance of the detector that occurs on decreasing T_0 from 4.2 to 1.5 K is independent of τ_{th} in the range $\tau_{th} = 0.1$–10 ms.

The compensated Ge bolometer has been subjected to a similar analysis. Using the values reported [5] for α_R and R in compensated Ge, the results show that for $\lambda_{on} < 60$ μm, the radiation fluctuation and Johnson noise term contributions are approximately equal, with the Johnson noise term becoming dominant for $\lambda_{on} > 100$ μm. The lowest NEP calculated for $T_0 = 1.5$ K is 4.8×10^{-14} W/Hz$^{1/2}$ which is about 3.7 times greater than the value obtained for Si.

CONCLUSIONS

The calculations reported in this paper show that the performance of a bolometer is very sensitive to the level of background radiation absorbed by the bolometer element, and that this dependence is due to the resistivity and thermal capacitance of the element being strong functions of temperature. These results also emphasize the need to state explicitly the optical detection system parameters, the background flux, and the thermal time constant when reporting on the NEP performance of a bolometer detector.

The present investigation shows that a high performance bolometer should be obtained from compensated Si with $N_D = 1.3 \times 10^{18}$/cm^3 and $K_n = 0.4$. Similarly, specimens with $N_D = 2 \times 10^{18}$/cm^3 and $K_n = 0.1$ and having a superior value for A_t, should yield good detectors, although the higher resistance at large values of λ_{on} may cause difficulty in obtaining a low-noise figure with available preamplifiers. The effects of the f number of the optical detection system, the size of the element, and the value for λ_{off} on detector performance are presently being investigated both for these two samples and other samples that were characterized in this study. This work together with a more detailed account of the calculations presented here will be the subject of a future publication.

In conclusion, the practical ultimate performance of a bolometer will be reduced by preamplifier noise and possibly by excess noise, such as current or contact noise generated in the element itself by the bias current. Preamplifier noise is expected to be small, because very good preamplifiers are commercially available for the range of detector resistances reported. The magnitude and source of any excess noise in Si bolometers is unknown at present, but the advanced state of Si device technology should be an advantage in enabling detector fabrication without excess noise [8].

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Submillimeter Heterodyne Detection and Harmonic Mixing Using Schottky Diodes

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***Abstract*—Schottky diodes have been used for submillimeter heterodyne detection and harmonic mixing. Using a carcinotron local oscillator at 890 μm, sensitive detectors of optically pumped lasers have been demonstrated up to fifth harmonic mixing at 1757.5 GHz. The measured noise equivalent power (NEP) in fundamenta mixing is approximately 10^{-16} W/Hz.**

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IN A recent publication [1], we have demonstrated that new low-capacitance small-contact-area GaAs Schottky diodes could provide high-order harmonic mixers at submillimeter wavelengths. Here we report the first application of these Schottky diodes as heterodyne detectors and low-order harmonic mixers of submillimeter