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OPTIMIZING INDIUM ANTIMONIDE (InSb) DETECTORS FOR LOW BACKGROUND OPERATION

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INTRODUCTION

Increased sensitivity of infrared detectors for astronomical applications is almost always desired. In the 1 to 5.6-μ region, the development of good photovoltaic indium antimonide (InSb) detectors has made possible a large increase in sensitivity over that of the previous PbS detectors. To realize the full potential of these detectors, however, one must understand the noise sources that limit their performance. It is the purpose of this note to review and discuss, as simply as possible, the various noise sources that affect the InSb detectors (and similar voltaic devices) so that their performance can be calculated. Various approximations and simplifications have been made in the treatment below; however, the results should be accurate enough for engineering purposes.

DETECTOR OPERATION

The operation of photo voltaic detectors has been described by Kruse et al. (ref. 1), but for this discussion we will treat the InSb detector as a current generator whose response to photons is given by

$$i = eN\phi \tag{1}$$

where

i current from detector, amperes

e electronic charge, 1.6×10^{-19} C

N number of photons with $\lambda < 5.6\ \mu$ striking the detector per second

ϕ quantum efficiency

Equation (1) should be replaced by an integral because ϕ is not independent of λ; however, for most applications ϕ can be assumed to be constant and of the order of 0.6-0.7.

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AMPLIFIER CIRCUIT

In order to achieve minimum noise, the detector is operated in a feedback circuit which keeps 0 V across the detector. This form of operation has been described by Hamstra and Wendland (ref. 2) and Hall et al. (ref. 3). The circuit is shown schematically in figure 1.

Z_F and Z_i represent the impedances of the feedback resistor and detector, respectively. The voltage (V^n) and current generators (i^n) are drawn explicitly because the amplifier responds differently to them (ref. 4). They represent either the amplifier voltage and current noises, the detector current, or injected test voltages. The amplifier usually consists of a cooled FET and a low noise op-amp (refs. 2, 3).

If we assume that the amplifier has infinite gain we can solve for the response to the voltage and current generators by noting that the output voltage will assume a value so that the input voltage to the op-amp equals zero.

$$v_{out} = i_{in} Z_F \tag{2}$$

$$v_{out} = v_{in}\left(1 + \frac{Z_F}{Z_i}\right) \tag{3}$$

The feedback resistor and the detector can both be represented by a resistor in parallel with a capacitor. The impedance is therefore complex; however, for rms measurements, which are insensitive to the phase, the modulus of Z_F and Z_i can be used

$$\left.\begin{aligned} |Z_F| &= \frac{R_F}{\sqrt{1 + (2\pi f R_F C_F)^2}} \\ |Z_i| &= \frac{R_i}{\sqrt{1 + (2\pi f R_F C_i)^2}} \end{aligned}\right\} \tag{4}$$

where

R_i, R_F are the resistances of the detector and the feedback resistor, respectively, ohms

C_i, C_F are the shunt capacitance of the detector and feedback resistor, respectively, farads (F)

f is the measurement frequency, hertz (Hz)

At low frequency the impedance becomes predominantly resistive

$$Z_F \to R_F \quad \text{for} \quad f < \frac{1}{2}\pi R_F C_F$$

$$Z_i \to R_i \quad \text{for} \quad f < \frac{1}{2}\pi R_i C_i$$

If there are other sources of capacitance, such as distributed capacitance of the feedback resistor to ground, the impedance cannot be represented by (4).

RESPONSE TO RADIATION

Because the detector acts like a current generator we have from equations (1) and (2)

$$v_{out} = iZ_F = eN\phi Z_F \tag{5}$$

Although when discussing photodetectors it is simpler to think in terms of photon number rates, it is more customary in infrared physics to measure detector response in terms of photon power. Defining the responsivity to monochromatic radiation of wavelength λ (microns) as the output voltage for a given input power P_{in}

$$\mathscr{R}_\lambda = \frac{v_{out}}{P_{in}} = \frac{eN\phi Z_F}{Nhc/\lambda} = 0.8\ \phi\lambda Z_F,\ \text{V/W} \tag{6}$$

Note that the responsivity is a function of λ, as well as the measurement frequency f, since Z_F is a function of frequency.

SOURCES OF NOISE

In order to get a useful figure of merit, we must compare the response of the detector to radiation to the level of the noise. It is convenient to think in terms of the noise currents instead of noise voltages because they can be compared directly to equation (1) without reference to the feedback resistance.

There are three primary noise sources:

1. Johnson noise of the detector and feedback resistor

2. Photon noise

3. Amplifier noise

In certain situations (usually high background), excess or current noise from the resistor may be important. The detector Noise Equivalent Power (NEP) is then

$$\mathrm{NEP} = \frac{i^n_{tot} Z_F}{\mathcal{R}_\lambda} = \frac{i^n_{tot}}{0.8\phi\lambda} \quad \mathrm{W/Hz^{1/2}} \tag{8}$$

where i^n_{tot} is the quadratic sum of all the noise currents.

Johnson Noise

The noise current density due to the thermal or Johnson noise from the feedback resistor and detector is

$$i^n_{detector} = \sqrt{\frac{4kT}{R_i}} \ , \ \mathrm{A/Hz^{1/2}}$$

$$i^n_{feedback} = \sqrt{\frac{4kT}{R_F}} \ , \ \mathrm{A/Hz^{1/2}}$$

where

T is the bath temperature, K

k is Boltzmann's constant = 1.38×10^{-23} J/K

Note that the noise current is due to the resistive part only, as reactive elements do not generate Johnson noise. The noise voltage outputs from the detector and feedback resistor can be found from equation (2). It is clear that the noise will be dominated by the smaller resistance and that a low bath temperature T is desirable.

Photon Noise

The random arrival of photons from the background radiation is another noise source. If the difference between Bose-Einstein statistics (ref. 1) and random arrival is neglected (a good approximation for $h\nu > kT$), then the noise current density due to fluctuations in the photon flux is

$$i^n_{photon} = \sqrt{2N\phi}\ e \ , \ \mathrm{A/Hz^{1/2}} \tag{9}$$

where N is the number of photons per second ($\lambda < 5.6$) striking the detector. The factor of $\sqrt{2}$ results from the fact that although the fluctuation in the number of photons arriving per second is $\sqrt{N\phi}$, in order to express this as a current density per $\mathrm{Hz}^{1/2}$ the $\sqrt{N\phi}$ must be multiplied by $\sqrt{2}$. (An additional factor of $\sqrt{2}$ in noise occurs in a photoconductive mode because a hole-electron pair is formed which subsequently recombines.)

The photon flux of N photons per second gives rise to a dc offset voltage

$$v_b = eN\phi R_F, \text{ V} \tag{10}$$

Inserting this in equation (9), we see that

$$i^n_{photon} = \sqrt{\frac{2ev_b}{R_F}} , \text{ A/Hz}^{1/2} \tag{11}$$

or in terms of noise voltage

$$v^n_{out} = i^n_{photon} Z_F \rightarrow \sqrt{2ev_b R_F} , \text{ V/Hz}^{1/2} \tag{12}$$

where the limit holds true for low frequencies. This equation is useful because from a measurement of the dc offset voltage due to a given background flux we can compute the noise voltage.

Amplifier Noise

The amplifier has both current and voltage noise; however, for an FET the latter is usually dominant. The output voltage due to amplifier noise voltage v^n_{amp} is (from eq. (3))

$$v^n_{out} = v^n_{amp} \left| 1 + \frac{Z_F}{Z_i} \right| , \text{ V/Hz}^{1/2} \tag{13}$$

The absolute value of v^n_{amp} is small (less than 1 μV) but it is amplified by the factor Z_F/Z_i, which for high frequencies becomes very much greater than unity. Converting equation (13) to find the equivalent noise current and neglecting the 1 in $|1 + Z_F/Z_i|$

$$i^n_{out} = \frac{v^n_{amp}}{Z_F} \simeq \frac{v^n_{amp}}{Z_i} \simeq v^n_{amp} 2\pi f C_i , \text{ A/Hz}^{1/2} \tag{13a}$$

Note that since the term v^n_{amp} is often proportional to $1/f^{1/2}$, the equivalent noise current will be proportional to $f^{1/2}$.

The amplifier also has current noise denoted i^n_{amp}. This should be low for a good FET; however, if there is gate current when operated back-biased this will give rise to a shot current density of

$$i^n_{amp} \simeq \sqrt{2ei_{gate}} , \text{ A/Hz}^{1/2} \tag{14}$$

The gate current can usually be made negligible by cooling the FET below room temperature, since the gate acts like a junction diode.

Resistor Current Noise

It has been observed that when current flows through a resistor there is often a noise, greater than the Johnson noise, with a 1/f power spectrum.

$$i^n_{resistor} = Ai/f^{1/2} \text{ , A/Hz}^{1/2} \qquad (15)$$

where

A   is an empirical constant depending on the resistor

i   is the current flowing through the resistor, amperes

f   is the frequency, Hertz

This noise is not to be confused with shot noise; resistors do not generate this form of noise. Although the mechanism that generates current noise is not well understood, current noise is known to be a function of the composition of the resistor and to vary from one unit to another (ref. 4). Havens (ref. 5) measured the current noise between 1-500 Hz of several Victoreen MOX-1125 type resistors; the results are shown in table 1. Measurements with both 20 V and 50 V yielded nearly identical values of A.

In the circuit shown in figure 1, the only time there is a current through R_F is when photons are incident on the detector. Comparing equations (9) and (15), we see that current noise predominates over photon noise when

$$\frac{Ai}{f^{1/2}} > \sqrt{2ei} \qquad (16)$$

This occurs usually only for high backgrounds; for example, if $R = 10^{10}$ ohms and $f = 10$ Hz, i must be greater than 1.2×10^{-7} A, a value greater than that allowed by most amplifiers; hence, we will neglect resistor noise in low background applications.

If a bias resistor is used to null out offset, it will add only Johnson and current noise (ref. 3). However, there is nothing wrong with eliminating this resistor and letting the output remain at an elevated voltage.

Excess Noise from the Detector

The preamplifier circuit is designed to maintain 0 V across the detector. However, it is clear that drifts will occur, and a finite voltage will then appear on the detector, giving rise to excess noise. The noise spectrum appears to be between 1/f and $1/f^2$. From measurements of the noise of one detector as a function of detector voltage, the noise can be modeled approximately by

$$i^n_{excess} = \frac{Bi_d}{f^{1/2}}, \text{ A/Hz}^{1/2} \tag{17}$$

where i_d is the current flowing through the detector due to the finite voltage and B is an empirical constant. We found that B is $\sim 10^{-4}$ to 10^{-3} for back bias and $\sim 10^{-3}$ for forward bias. It is not clear whether this number is representative of all detectors or indeed if equation (17) is a good model. However, for a dual FET design the drifts are usually small enough that the excess noise is dominated by other noise sources.

MEASURING AMPLIFIER AND DETECTOR PERFORMANCE

The important amplifier and detector parameters are:

1. Detector resistance, R_i
2. Photon loading of the detector, N
3. Detector and amplifier input capacitance, C_i
4. Amplifier frequency response, related to C_F
5. Amplifier noise, v^n_{amp} and i^n_{amp}
6. Quantum efficiency

This section describes how to measure the above parameters. Most of the tests are performed by injecting a test voltage into the (+) input of the op-amp (fig. 1) in order to simulate the voltage generator v_{in}. In a dual FET circuit such as that of Hall et al. (ref. 3), the voltage is placed on the gate of the reference FET.

Detector Resistance R_i

By injecting a dc voltage (or by adjusting the offset pot in the circuit of Hall et al. (ref. 3)) and measuring the change of output voltage as a function of input voltage, we find from equation (3) that

$$R_i = \frac{R_F}{\left[\left.\frac{\Delta v_{out}}{\Delta v_{in}}\right|_{v_{in}=0} - 1\right]}$$

The detector resistance should be measured with 0 V across the detector, hence the differential notation above. The point at which 0 V is on the detector occurs when the noise is at a minimum and is near or at the point at which the resistance is a maximum.

Photon Loading

The photon loading is the output voltage from the amplifier when the voltage across the detector is zero. This corresponds to a photon flux as determined by equation (10).

Detector and Amplifier Input Capacitance

The detector capacitance (in parallel with amplifier input capacitance) is measured in the same way as R_i, but instead of injecting a dc voltage, a small ac voltage of known frequency and amplitude is used. Then equation (3) is used to find $|Z_i|$ then C_i. This simplified, however, for $(1/2)\pi C_i R_i < f < (1/2)\pi R_F C_F$ to

$$C_i = \frac{1}{2\pi f R_F}\left(\frac{\Delta v_{out}}{\Delta v_{in}} - 1\right)$$

Amplifier Frequency Response

One method of measuring the frequency response of the amplifier is to send radiation onto the detector and to measure the response at different chopping frequencies. However, the frequency response can also be determined with the detector disconnected by measuring the spectrum of the Johnson noise of the feedback resistor, which will be the same function of frequency as the responsivity. If the feedback impedance consists of a resistor in parallel with a capacitor, the frequency response will be that of a single RC circuit as given by equations (4) and (6). If distributed capacitance to ground is important, there can be a maximum in the frequency response at some frequency. This shows up quite clearly in the response to a square wave as an overshoot followed by ringing. If this is the case, equation (4) does not represent $|Z_F|$.

Amplifier Noise

The amplifier noise can be measured by replacing the detector with a large (~1000 pF) low noise polystyrene capacitor and measuring the output noise. This large reactance increases the amplifier noise but does not add Johnson noise. The amplifier noise is then found from equation (13). A large feedback resistor ($>10^{10}$ ohms) is needed to bring the amplifier noise above the Johnson noise.

The circuit in figure 1 assumes that the gain of the amplifier is infinite. This is, of course, not true in practice, particularly at higher frequencies. When measuring amplifier noise do not use capacitors that are so large that R_F/Z_i is of the same order as the amplifier gain. A treatment of finite gain is given by Neiswander and Plews (ref. 6).

Current noise will show up as an excess over Johnson noise when very high feedback resistors are used and the detector is disconnected. If the gate current is a problem, it can be measured with an electrometer.

Quantum Efficiency

The quantum efficiency has to be measured by illuminating the detector with a known number of photons per second and using equation (1). Since the detector responds to dc, a digital voltmeter can be used to get an accurate measurement of v_{out}.

NUMERICAL EXAMPLE

To illustrate the discussion above, we consider an InSb detector with the following characteristics

0.5-mm diam

$R_i = 6\times10^8$ ohms

$C_i = 100$ pF

$\phi = 0.6$

This detector has a resistance-area product of 1.2×10^6 ohm-cm^2, a value readily available in commercial detectors. The junction capacitance is typical of InSb detectors of about 500 pF/mm^2. Smaller detectors will lead to lower NEP; however, the area of the contacts must be included in calculating R_i or C_i.

Johnson Noise

At 77 K, the Johnson noise current of the detector is (eq. (7))

$$i^n = 2.66\times10^{-15}\ \text{A/Hz}^{1/2}$$

It has been found that the resistance of InSb detectors can be increased by "flashing" or exposing them to radiation of 1.6 μ (such as from a GaAs LED) and operating at 63 K with pumped LN_2; different detectors have different characteristics. The mechanism responsible for this induced increase in resistance is unknown to the author. With this procedure the RA product can be increased to about 2×10^{8} ohm-cm^2 or for the 0.5-mm detector, $R_i = 10^{11}$ ohms. The Johnson noise for such a detector at 63 K is then

$$i^n = 1.85\times10^{-16}\ \mathrm{A/Hz^{1/2}}$$

InSb detectors can be operated at liquid helium temperature. The quantum efficiency may remain unchanged, but the cutoff wavelength will decrease. Goebel (private communication from J. Goebel, NASA-ARC) has pointed out that the catastrophic drop of quantum efficiency reported by Hall et al. (ref. 3) was probably due to the failure of the 2N6484 JFET at low temperature. MOSFET's can be used at liquid helium temperatures but their voltage noise usually offsets the gain obtained at lower temperatures. However, assuming the 0.5-mm flashed detector mentioned above and operating at 4.2 K, the Johnson noise current of the detector is

$$i^n = 4.77\times10^{-17}\ \mathrm{A/Hz^{1/2}}$$

To get full advantage of the detector resistance, the feedback resistance must be greater than the detector resistance. For this example, we will assume that $R_F = 3\times10^{11}$ ohms with a shunt capacitance of 0.12 pF. This causes serious degradation of the frequency response; for this case $f_{3db} = 4$ Hz. However, it can be shown that the noise will decrease by the same factor as the responsivity, and therefore the NEP will not suffer. If flat frequency-phase response is needed, a treble-boost circuit such as that discussed by Neiswander and Plews (ref. 6) can be used. Note that this will hold for frequencies where R_F/Z_i is a small fraction of the amplifier gain. In this way, detector capacitance can limit the maximum frequency response.

Amplifier Noise

Figure 2 shows v^n_{amp} for the circuit given by Hall et al. (ref. 3). Extra shunt capacitance was added to the offset circuit to suppress the Johnson noise of the 10 K resistor. The noise measurements were made with an Ithaco Model 391A using the method described above. A variation was observed between the 2 FETS tested, although there is little difference in noise between room and LN_2 temperatures. Using equation (13) to convert the data, the equivalent noise current at 20 Hz due to the amplifier is

$$i^n_{amp} = \frac{v^n_{amp}}{Z_i} = \frac{22\ \mathrm{nV/Hz^{1/2}}}{7.96\ 10^7\ \Omega} = 2.76\times10^{-16}\ \mathrm{A/Hz^{1/2}}$$

The noise current does not increase linearly with frequency because v^n_{amp} decreases with f.

This circuit uses a dual FET input in source follower configuration. If a single FET were used, the noise would decrease by a factor of $2^{1/2}$ although the circuit would be more susceptible to drift and therefore excess noise.

One can also use two or more FETS in parallel and reduce the noise further by the square root of the number of FETS (ref. 6). However, each FET increases the input capacitance C_i by ~8 pF and so the decreased noise will be offset by increased amplification; therefore, two FETS in parallel probably represent a realistic maximum.

Photon Noise

The high sensitivity of InSb detectors means that great care must be given to reducing the background loading of the detectors. For example, a system with throughput of 4.5×10^{-5} cm^2-sr (a typical value for astronomical applications) and with a cooled filter transmitting from 2.1-2.3 μ will have a photon flux from a 300 K blackbody of $N = 8.61\times10^6$ photons/sec. This will yield a current noise (eq. (9))

$$i^n_{photon} = 5.14\times10^{-16} \text{ , A/Hz}^{1/2}$$

Collecting all the noise sources and assuming a "flashed" detector operating at 63 K, we obtain the noise levels shown in table 2.

The current responsivity is (eqs. (2) and (6))

$$\mathcal{R} = 1.06 \text{ A/W}$$

So the 2.2 μ NEP (from eq. (8)) is

$$NEP = 7.95\times10^{-16} \quad \text{W/Hz}^{1/2}$$

$$= 5.77\times10^{-16} \quad \text{without photons}$$

Consequently, the detector is almost background-limited.

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TABLE 1.- CURRENT NOISE OF RESISTORS

R, ohms	A
10^{10}	5.2×10^{-6}
10^{9}	5.4×10^{-7}
10^{8}	2.1×10^{-7}

TABLE 2.- NOISE SOURCES FOR InSb DETECTOR

Source	Noise, $A/Hz^{1/2}$
Johnson noise R_F	1.08×10^{-16}
Johnson noise R_i	1.85×10^{-16}
Amplifier noise, 20 Hz	2.76×10^{-16}
Photon noise	5.14×10^{-16}
Total	6.21×10^{-16}

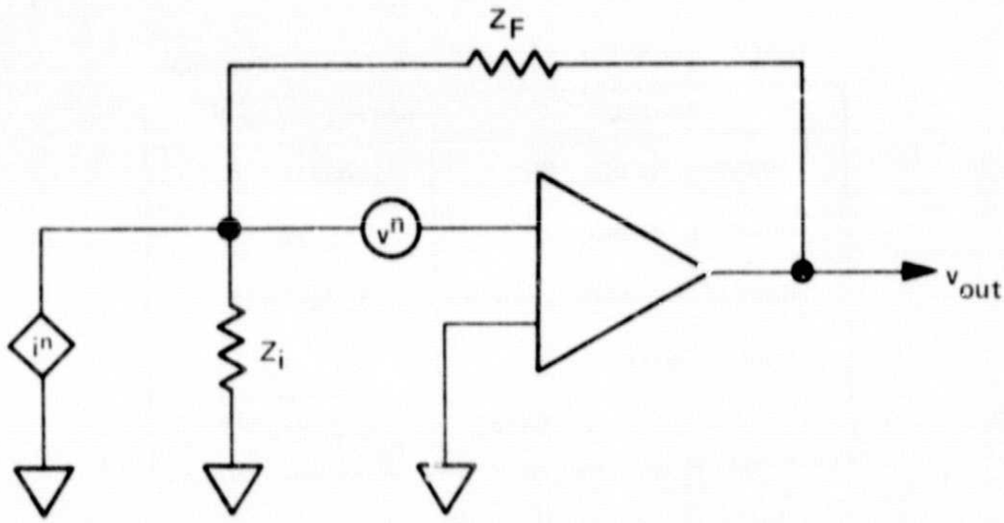

Figure 1.- Detector amplifier circuit.

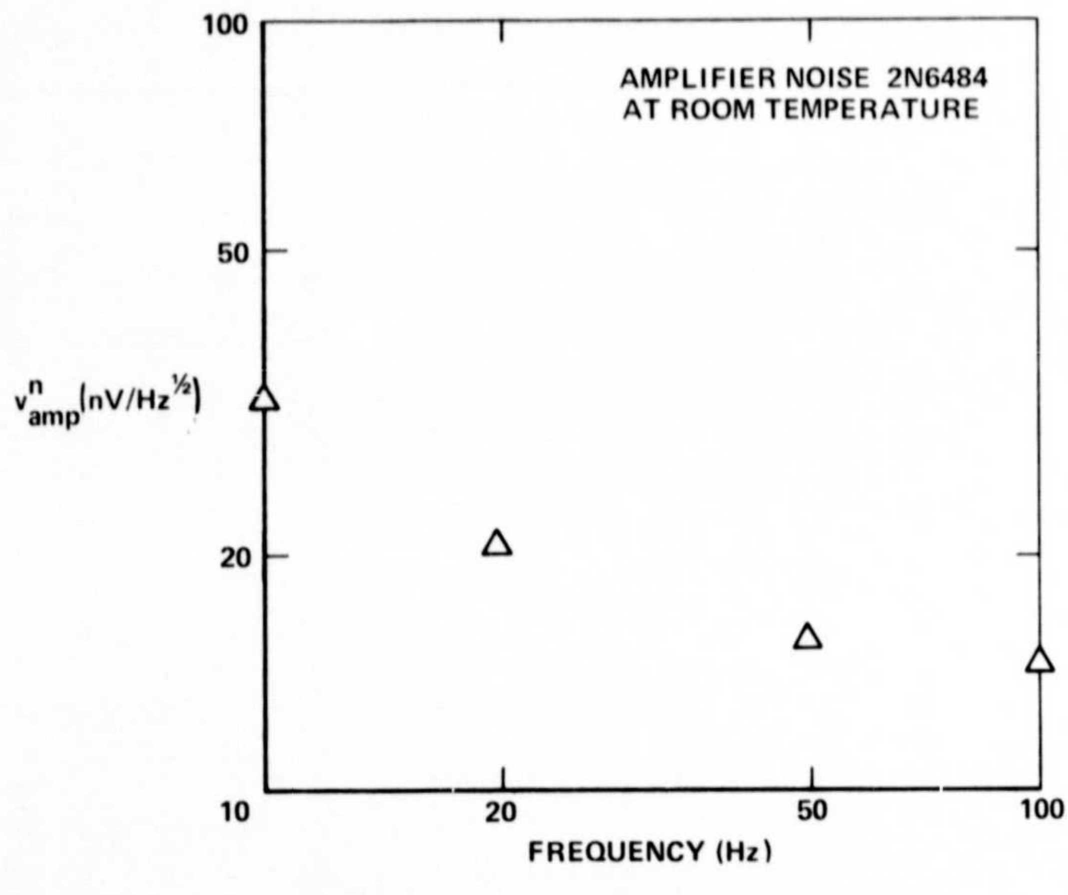

Figure 2.- Measured amplifier noise vs frequency.