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HIGH SENSITIVITY OPERATION OF DISCRETE SOLID STATE DETECTORS AT 4 K

G. H. Rieke*, E. F. Montgomery+, M. J. Lebofsky+, and F. R. Eisenhardt+

Abstract

Techniques are described to allow operation of discrete, solid state detectors at 4 K with optimized JFET amplifiers. Three detector types cover the 0.6 to 4 μm spectral range with NEP $\sim 10^{-16}$ $Hz^{-½}$ for two of the types and potential improvement to this performance for the third. Lower NEPs can be anticipated at longer infrared wavelengths.

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* University of Arizona, Steward Observatory and Lunar & Planetary Lab.

Alfred P. Sloan Fellow

+ University of Arizona, Steward Observatory

I. INTRODUCTION

An amplifier to optimize the performance of discrete, solid state detectors has been discussed by Wendland[1] and Wyatt, Baker, and Frodsham.[2] Based on a concept originally discussed by Perchowitch and Zaalberg von Zelst,[3] this circuit uses feedback to maintain the linearity of the detector over a large dynamic range, to improve the frequency response, and to control the bias voltage. Hall et al.[4] demonstrated that excess noise in photovoltaic InSb detectors could be eliminated with this amplifier if the bias voltage across the detector is held close to zero. Operated in this manner, these detectors have defined the state of the art for low light level detection between 1 and 5 μm. Substantial improvement has been achieved over the performance level discussed by Hall et al.,[4] primarily by selecting detectors for high impedance and developing methods for increasing the impedance further.[5,6] The detectors are now usually operated at a temperature near the triple point of liquid nitrogen (63 K), with feedback resistors up to 10^{12} ohms, and after exposure to intense radiation at 1 μm. For most applications between 3 and 5 μm, the detectors are background limited, and since they have high quantum efficiency ($\sim$ 60%) and are free of recombination noise, they approach the theoretical limit to performance.

Nonetheless, the detection approach described above has shortcomings in some applications. For very low backgrounds, such as those usually encountered in astronomical applications between 1 and 2.5 μm, the necessary selection of detectors can be expensive and time-consuming. The very large feedback resistors required for maximum sensitivity severely limit frequency response and dynamic range. Providing for exposure to 1 μm radiation can complicate system design. Frequently, it is desirable to operate InSb detectors in arrays with other types of infrared detector at temperatures near 4 K. Barton and Allen[7] have described a preamplifier which overcomes the limitations in frequency response and dynamic range inherent in the type of preamplifier described by Hall et al.,[4] without sacrificing sensitivity. Even with this amplifier, the other disadvantages of operating at liquid nitrogen temperature remain. Some of these same disadvantages also apply with other detector types operated in the near infrared at liquid nitrogen temperatures, and virtually all sensitive detector types beyond 5 μm require cooling to lower temperature.

This paper discusses the operation of InSb, Silicon PIN diodes, and germanium photodiodes at 4 K. Peak NEPs of $\sim 10^{-16}$ $WHz^{-\frac{1}{2}}$ have been achieved with PIN diodes and InSb, and one InSb detector system has been in operation for astronomical photometry for two years, during which period it has exhibited exceptionally high stability. A further development of the general techniques discussed here is being used for the detector array for the Spacelab Infrared Telescope (Gautier et al.[8]), where Johnson-noise limited performance at 10^{10} Ω is obtained from 4 to 120 μm with low-background photoconductors in a spaceflight-qualifiable package.

II. PREAMPLIFIER DESIGN

The preamplifier used by us is very similar in electronic design to that developed by Hall et al.;[4] a circuit diagram is shown in Figure 1.

The detector and feedback resistor are thermally sunk to the work surface of a liquid helium dewar. The low noise of JFETs as opposed to MOSFETs dictates their choice as the cooled first stage of the amplifier. Since JFETs are inoperative below $\sim$ 55 K, the transistors are mounted within the dewar close to the detectors, rigidly attached with an insulating support to the helium-cooled work surface but thermally strapped with a copper braid to the liquid-nitrogen-cooled radiation shield of the dewar. A short constantin lead (typically 1 cm long) connects the detector to the gate of one FET; amplifier instabilities caused by stray capacitance are minimized by keeping this lead as short as possible and not glueing it to any metallic surfaces. This mounting arrangement, shown in Figure 2, is the key to successful operation of the amplifier, since it eliminates microphonics associated with differential motions of the detector and JFET while allowing each unit to be operated at its optimum temperature.

An extensive search was conducted to determine the best available JFET type for this application; the results are summarized in Table 1. In the course of this testing, it became obvious that there are large variations in low temperature performance, not only from type to type but from FET to FET of the same type. We were only able to test a small sample of each type; in general, we bought 10 FETs of each type and tested fully the 2 or 3 of these 10 which had the lowest noise at room temperature. It would therefore not be surprising if better results were obtained from additional samples of a FET that performed poorly in our tests. Nonetheless, the 2N6484-E230-J230 FET clearly emerged as a superior family for this application, due to its low leakage current and low noise at temperatures near 70 K. The gate capacitance of these FETs is typically only a few pfd.

The noise measurements in Table 1 were obtained by operating the FETs as source followers with grounded gates. The sources were connected through a 40 K resistor to - 9V and the drains directly to + 9V. The output was connected to a low noise gain-of-1000 amplifier, a tuned electronic filter, and an RMS AC voltmeter. The voltmeter output was integrated digitally for up to 10 minutes to increase the accuracy of measurement. The contribution of the gain-of-1000 amplifier, measured by shorting its input, was subtracted quadratically from the total noise measured. The equivalent input noise of this amplifier was 5 $nVHz^{-\frac{1}{2}}$, less than the noise of any of the FETs tested at low temperature. The noise measurement system was calibrated from the Johnson noise of a 40,000 ohm wirewound resistor connected to the input of the gain-of-1000 amplifier.

Most of the FETs were tested for noise as a function of temperature near 10 Hz. The temperature was sensed with a calibrated diode (Lake Shore Cryotronics, Inc., Westerville, Ohio); the diode, FET, and a resistive heater were mounted on an insulating standoff within the dewar. Qualitatively, all of the FET types had remarkably similar behavior in this test; the noise was near minimum at room temperature, rose to a maximum near 200 K, had a minimum near 115 K, another maximum near 95 K, and was low again below 80 K, until the FET turned off slightly below 60 K. The amplitude of the noise variations with changing temperature changed dramatically from type to type and FET to FET, within this qualitative framework. The transconductance of the FETs has a maximum near the noise minimum at 115 K, so this temperature would be optimum for many applications. Our choice to sink the FETs to the liquid nitrogen bath was to simplify construction of the detector systems and to provide rapid equilibration and good stability of the system performance.

The leakage current was determined by measuring the swing in output voltage of the FET in a source follower configuration while a latching relay was used alternately to ground the gate and to connect a 10^{12} Ω resistor from the gate to ground. Again, the source resistor was 40 K Ω and the supply voltages plus and minus 9V.

Since the JFETs are used in matched pairs, the dual transistor 2N6484 is attractive for the first stage of the preamplifier. However, many of these transistors have high impedance leakage paths between various pins or a pin and the case; good results were obtained more reliably by selecting J230s for closely matched DC characteristics when dipped in liquid nitrogen. The cold J230s in the preamplifier are operated with a small voltage gain (factor of 3 to 5) in order to insure that the other amplifier components do not add to the noise imposed by the first stage.

The cooled Eltec chip resistor (Eltec Inst., Inc., Daytona Beach, Fla.) is mounted close to the detector. These resistors become increasingly nonlinear as the temperature is reduced. It is desirable to select chips with small temperature coefficients of resistance and good linearity (these two parameters are strongly correlated). A substantial effort in developing our preamplifier was devoted to selection and calibration of the feedback resistor. The best amplifier linearity is obtained in the frequency regime where the feedback impedance is predominantly capacitive. For small values of the feedback resistor and low signal frequencies, it may therefore be advisable to add capacitance to the feedback resistor. Suitable capacitors can be made from copper clad circuit board.

The dynamic range of the amplifier can be extended by switching feedback resistors. The Teledyne miniature latching relay J420-26WL can be operated at liquid nitrogen temperature and is well suited for this purpose. The frequency response of the amplifier can be compensated by a following stage. The amplifier is powered by two 9 volt batteries.

The measured frequency response of the amplifier coincides closely with that predicted from the RC time constant of the feedback, assuming an effective capacitance of 0.1 pf for the feedback resistor. Independent measurements of the capacitance of the resistors in the mounting configuration used indicates a value of 0.1 pfd. The noise is limited by the 4 K Johnson noise of the feedback resistor for resistances $< 3 \times 10^{11}$ ohms for at least an octave above tne knee in the frequency response. For feedback resistors larger than $3 \times 10^{11}\ \Omega$, there is excess noise with the same frequency dependence as the signal, and increasing in magnitude linearly with the value of feedback resistance.

The frequency dependence of the excess noise suggests a current "shot noise" mechanism. The measured shot noise from the 10^{12} ohm resistor is dependent on operating temperature, being about 20% of the classical prediction (i.e., given by the square root of the number of electrons required to flow to produce the current) at room temperature, and about 5% of this prediction at 4 K. The current noise associated with the gate leakage from the FET would therefore only be $2\ \mu V\ Hz^{-1/2}$, if the gate were an ideal current source. If the gate conduction mechanism is subject to the full classical shot noise prediction (i.e., conduction is as if by independent electrons), a current noise of $50\ \mu V\ Hz^{-1/2}$ would result, twice the observed excess. Since the excess noise lies between these two limits, it is plausible to associate it with the gate leakage current.

When used with practical detectors, the preamplifier is subject to three forms of excess noise. If the detector impedance is less than that of the feedback resistor, it can produce excess Johnson noise. If the detector has a large capacitance, the equivalent input noise will be amplified with increasing frequency. Finally, the currents required to establish a critical detector operating parameter may contribute additional noise.

III. DETECTORS

Three detector types have been tested with this preamplifier: silicon PIN diodes (United Detector Technology, Santa Monica, Calif.), germanium photodiodes (Rofin Optics and Electronics, Newton Upper Falls, Mass.), and photovoltaic InSb (Santa Barbara Research Center, Goleta, Calif.). The results are summarized in Figure 3. At 4 K, detectors of all three types that had been selected by their manufacturers for high impedance were found to have impedances > 10^{12} ohms. Therefore, Johnson noise from the detectors was smaller than the preamplifier noise.

With a 0.5 diameter silicon diode, the preamplifier noise performance was not significantly degraded at low frequencies; the responsivity was $\sim$ 0.3 A/W, and the measured NEP was 1.3×10^{-16} W $Hz^{-\frac{1}{2}}$ at 2 Hz. A photometer was constructed and the level of sensitivity measured in the laboratory was confirmed by observations of calibrated stars.

With the germanium diode, the noise performance was degraded by a factor of $\sim$ 1.5 at 2 Hz. The NEP increased proportionally to frequency above 2 Hz. This behavior is as would be expected if the detector had a capacitance of $\sim$ 150 pfd, although the manufacturer specifies a value of only $\sim$ 40 pfd. However, our own measurements yielded a capacitance of $\sim$ 100 pfd for the diode at 77 K, in good agreement with the value deduced from the performance of the preamplifier. The detector tested was 1 mm in diameter, the smallest supplied by the manufacturer. Smaller germanium diodes would give substantially better performance, particularly at frequencies higher than 2 Hz. The responsivity of the detector was only $\sim$ 0.1 A/W at 4 K and much lower at room temperature. The manufacturer's specification is 0.5 A/W, so that it is possible that a second sample would perform much better than the one tested.

With 0.3 mm square InSb detectors, after the detector bias has been set to minimize the noise, a substantial excess remains. At low frequencies, the frequency dependence of this noise is identical to that of the signal, so the NEP is independent of frequency. Near the frequency predicted from the detector capacitance ($\sim$ 50 pfd) and FET noise, the NEP begins to increase as the input noise of the preamplifier begins to dominate. A current of nearly 10^{-12} amp must pass through the feedback resistor to set the optimum operating point (i.e., maximum impedance) for the InSb detectors. This current is needed because the maximum impedance evidently does not correspond exactly with zero bias on the detector. The excess noise of $\sim$ 75 μV Hz$^{-1/2}$ (referred to DC frequency response) corresponds roughly to the expected excess from this current. It decreases the performance of the detector-preamplifier combination by about a factor of three.

The spectral responses of the three detector types operated at 4 K are shown in Figure 3. In all cases, at this low operating temperature the response curves are shifted slightly blueward. Except for this effect, the responsivities and quantum efficiencies are essentially unchanged between room temperature and 4 K for the silicon diodes and between 77 K and 4 K for InSb.

IV. CONCLUSION

Techniques have been developed to allow operation of a discrete solid state detector at 4 K with a carefully optimized JFET first amplifier stage. With an ideal detector and at low frequencies (~ 2 - ~ 30 Hz), the amplifier performance is limited by Johnson noise in the feedback resistor (held at 4 K) for resistances $< 3 \times 10^{11}\,\Omega$. With practical detectors, the noise performance can be degraded by additional Johnson noise, shot noise, or by amplification of the noise of the JFET (if the detector capacitance is large). With three types of near infrared detector (PIN silicon diode, germanium diode, and InSb diode), the behavior of the detector-preamplifier combination can be predicted accurately from knowledge of the electrical properties of the detector and preamplifier components. All three detector types appear to be capable of achieving NEPs of $\sim 10^{-16}$ W Hz$^{-1/2}$ with this preamplifier. Because relatively smaller feedback resistors can be used, this mode of operation permits greater dynamic range and better frequency response than are possible operating similar detectors at higher temperatures to comparable levels of sensitivity. Detectors that reach impedances $> 10^{12}$ ohms at 4 K are readily available for all three types tested; at higher temperatures, lower impedances are more typical. Two disadvantages of this method of operation are the expense and complication of cooling to 4 K and a shift of the spectral response of the detectors toward the blue.

The approach described in this paper should be applicable to virtually all types of discrete photoconductive and photovoltaic solid-state detectors. Because they are available with larger responsivities, mid- and far-infrared detectors should achieve even better NEPs than reported here.

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Table 1. JFET Performance

FET Type	Manufacturer	Noise at 10 Hz ($nV\ Hz^{-1/2}$) (1) 300 K	115 K	77 K	Leakage (Amp) 300 K	77 K
2N 3369	Siliconix	>40	--	--	--	--
2N 4416	Siliconix	33	--	--	--	--
2N 5197	Siliconix	11	∿15	53	4×10^{-13}	2×10^{-16}
2N 6484 (2)	Intersil	11	--	10	5×10^{-14}	2×10^{-15}
E 230 (2)	National	5	5	5	--	--
J 230 (2)	National	10	12	6	6×10^{-13}	6×10^{-15}
U 403	Siliconix	10	∿20	25	2×10^{-13}	4×10^{-14}
U 431	Siliconix	9	--	43	5×10^{-13}	1×10^{-12}

(1) Noise measurements are for individual samples selected for low noise at 300 K.

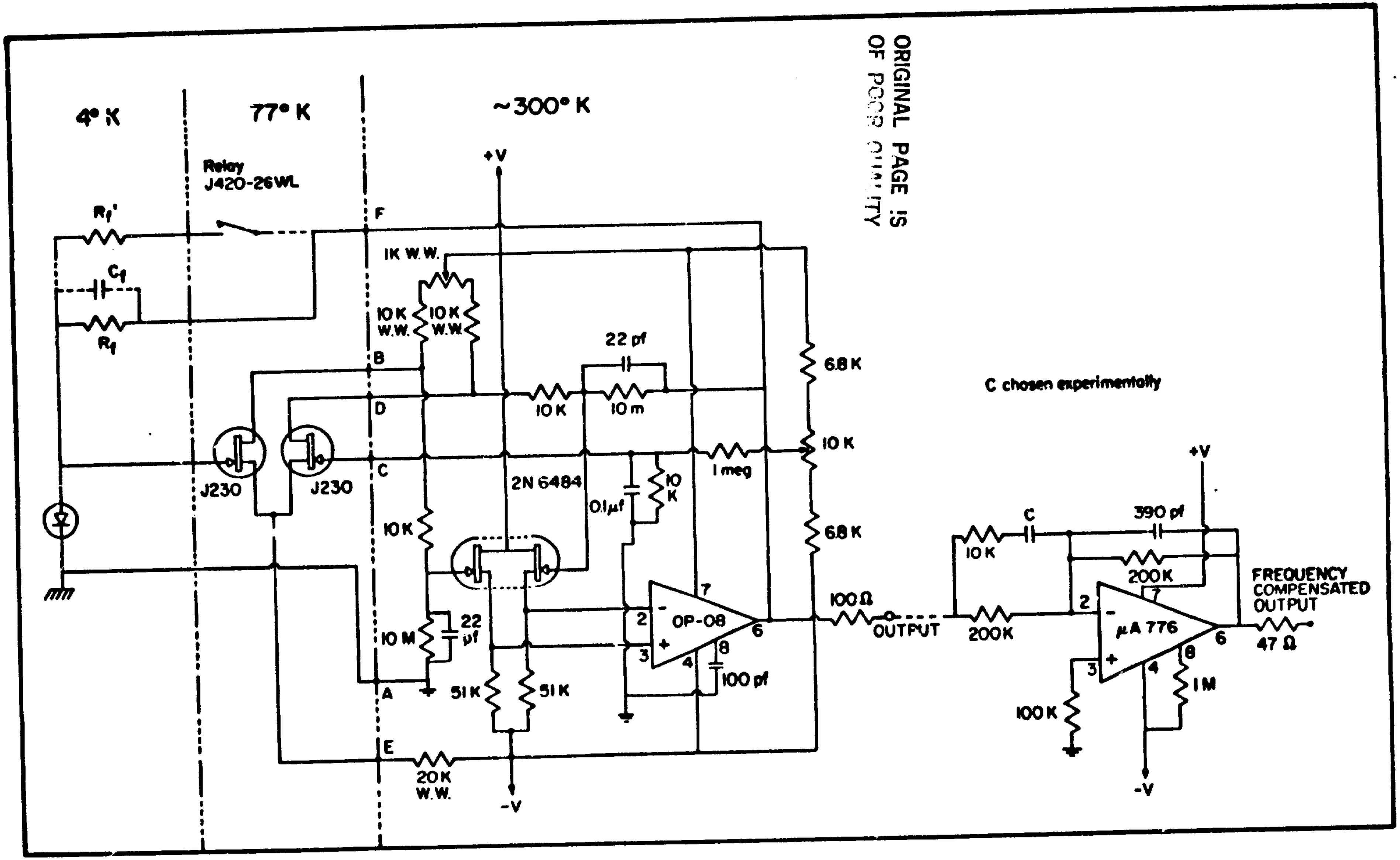
(2) 2N 6484, E 230, and J 230 share the same chip geometry.

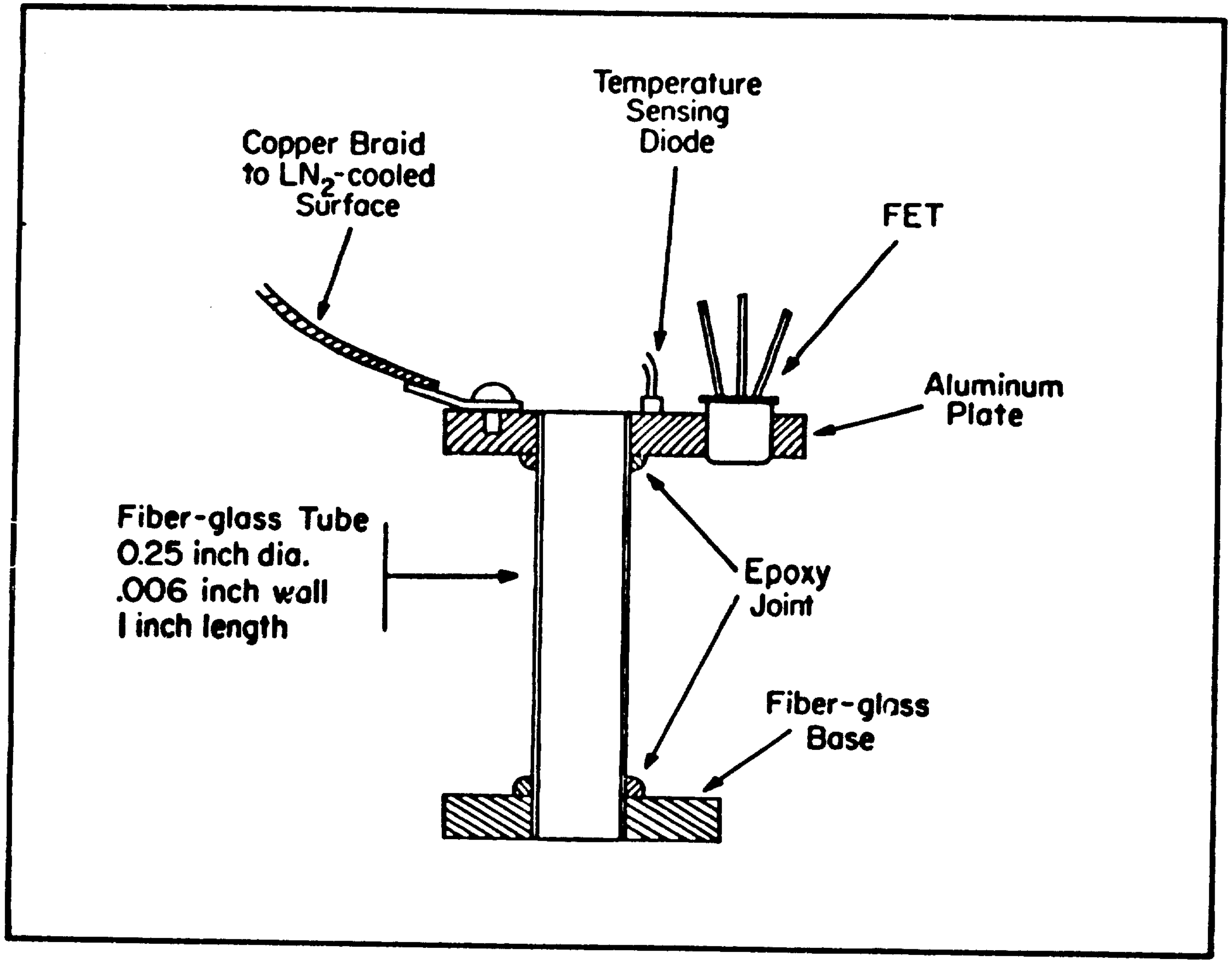
FIGURE CAPTIONS

Figure 1. Preamplifier Circuit Diagram. Optional parts of the circuit are shown connected with dashed lines.

Figure 2. Mounting of FETs to 4 K Surface.

Figure 3. NEPs for Three Detector Types at 4 K. The solid line is a silicon PIN diode, dotted line a germanium photodiode, and dot-dashed line an InSb photodiode. The indicated performance was obtained at 2 Hz for the germanium detector and from 2 to ~ 30 Hz for the other types. The vertical arrow shows the expected improvement for a germanium detector of higher responsivity (see text). The dashed curves show the red portion of the spectral response curves of the detectors at 300 K for the silicon and germanium diodes and at 77 K for InSb. Most of the spectral shift for the first two detector types occurs between 300 K and 77 K. The dashed curves are normalized to a wavelength where there was little change in spectral response with operating temperature, and are not meant to indicate a level of performance actually attained at the higher temperature.


4° K
77° K
~300° K
Relay
J420-26WL
R_f'
C_f
R_f
J230
J230
F
B
D
C
A
E
1K W.W.
10 K
W.W.
10 K
W.W.
+V
22 pf
10 K
10 m
2N 6484
0.1μf
10
K
1 meg
10 K
10 M
22
μf
51 K
51 K
20 K
W.W.
-V
OP-08
7
2
3
4
8
6
100 pf
6.8 K
10 K
6.8 K
100Ω
OUTPUT
C chosen experimentally
10 K
C
390 pf
200 K
200 K
+V
μA 776
1 M
100 K
-V
FREQUENCY
COMPENSATED
OUTPUT
47 Ω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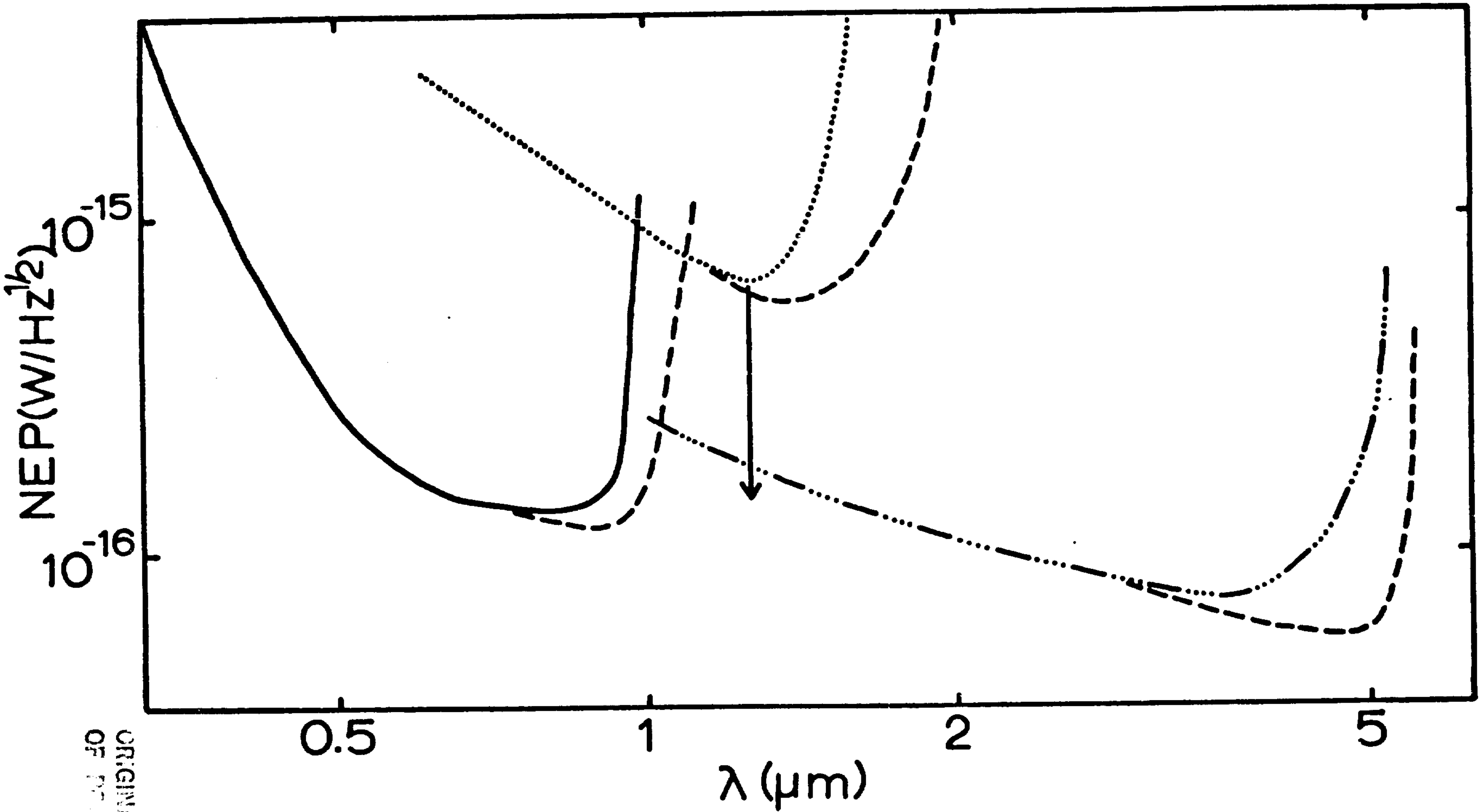
Temperature Sensing Diode
FET
Aluminum Plate
Fiber-glass Tube 0.25 inch dia. .006 inch wall I inch length
Epoxy Joint
Fiber-glass Base



NEP(W/Hz$^{1/2}$)
10^{-15}
10^{-16}
0.5
1
2
5
λ (μm)