Cryogenic Parametric Amplifier Noise Performance at 4.2K

WILLIAM J. WILSON, ROBERT L. DICKMAN, AND GERALD G. BERRY

***Abstract*—Results of an experiment in which a 4.5--5.0-GHz paramp was operated at 4.2 K are reported. The measured noise temperature at 4.2 K was 12 K. This is 6 K lower than the unit's noise temperature at its normal operating point of 18 K. It is concluded that varactor heating by the pump oscillators limited the improvement in noise performance. Prospects for further improvements in paramp noise temperature using better varactors are discussed.**

I. Introduction

LOW NOISE amplifiers are required in many areas of communications, radar, and radio astronomy. One important application is their use as first IF amplifiers in millimeter-wave mixer receivers, where mixer conversion losses are large but mixer noise temperatures are small. In this case low noise IF amplifiers ($T_{amp} < 10$ K) are required to achieve optimum receiver noise performance. Examples of such receivers include conventional cooled mixers [1], [2], superconducting Schottky mixers [3], varactor down converters [4], and quasi-particle superconducting mixers [5].

The lowest noise amplifiers presently available are masers operated at liquid helium temperatures, with noise temperatures $\leqslant 4$ K. However, these are complex devices, requiring a major investment in equipment and expertise to achieve this noise performance. They also have small percentage bandwidths, making them unsuitable for some applications.

Another possibility for very low noise performance is the cryogenic parametric amplifier. Cooled paramps have been developed which have noise temperatures of $\leqslant 15$ K when cooled to an ambient temperature of 18 K. If paramp noise is primarily thermal in origin, noise temperature should continue to decrease at temperatures below 18 K. However, uncertainties regarding ferrite circulator losses at very low temperatures, and the effects of varactor heating by the pump oscillators make any predictions of noise temperature at reduced temperatures very uncertain. This paper reports the results of an experiment to determine the noise properties of two paramps operated at liquid helium temperatures (4.2 K).

II. Measurements

Two paramp stages were used for the experiment to reduce the noise contribution from following stages. The paramps were early models of a unit that was designed by the Applied Electronics Division, Airborne Instruments Laboratory (AIL), Melville, NY, under contract to the National Radio Astronomy Observatory for use in the very large array (VLA) radio telescope. They were provided on loan by AIL. Specifications for the production amplifiers are given in Table I. (The prototype units used in this experiment had a slightly higher noise temperature of 18 K.)

The paramps were mounted on a copper heat sink inside a sealed can, which was placed near the bottom of a liquid helium dewar. The sealed can reduced thermal stresses caused by liquid helium boiling. Special care was taken to heat-sink the varactor mounts to ensure the lowest possible varactor temperature. A block diagram of the experimental setup is shown in Fig. 1 and a photograph of the paramp assembly is shown in Fig. 2.

The paramps are pumped at 26.3 GHz, and normally use Gunn diode oscillators with an output power of 75 mW. In the present experiment, a 120-cm run of WR-28 copper waveguide, having a 30-cm insert section of thin-wall gold-plated stainless steel waveguide (for thermal isolation) was used to connect each amplifier to its pump source. Each pump waveguide has a loss of ~1.8 dB when cooled. Because of these losses, it was necessary to use klystrons as pump sources. Based on power measurements of pump klystron No. 1 and the reflected power from varactor No. 1, it was calculated that ~40 mW of power was dissipated in each varactor circuit when the paramps were cooled to 4.2 K. The temperature of the varactor housing was monitored, and an 0.1–0.2 K temperature rise was noted when the pump power was applied.

During the initial series of measurements it was observed that when LHe was transferred into the dewar, the paramp bandpass changed radically and a large amount of pump power (~350 mW) was required to achieve proper amplifier gain and bandpass. Most of this power (~250 mW) was found to be reflected by the varactor assembly. Slight adjustment of the pump frequency (by ~200 MHz) reduced the power requirements by ~9 dB and lowered the reflected power correspondingly. This large mismatch in the pump circuit was attributed to leakage of LHe through the solder seals of the can and into the varactor cavity, causing its dielectric constant to change.[1] In subsequent measurements, special care was

Manuscript received May 3, 1979; revised October 15, 1979. This work was supported by the Aerospace Corporation.

The authors are with the Electronics Research Laboratory, the Aerospace Corporation, Los Angeles, CA 90009.

[1]The dielectric constant of liquid helium is 1.048. A shift of ~400 MHz in pump resonant frequency would be expected if liquid helium completely filled the varactor cavity.

0018-9480/80/0300-0186$00.75 ©1980 IEEE

TABLE I
SPECIFICATIONS OF AIL PARAMPS

Center Frequency	4750 MHz
Bandwidth	500 MHz
Gain	13 dB per stage
Pump Frequency	26.3 GHz
$T_{ambient}$	18 K
T_{paramp}	15 K

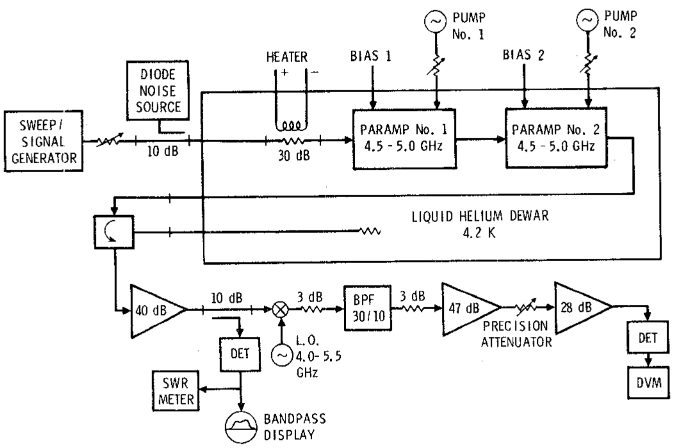

Fig. 1. Block diagram of paramp noise measurement system.

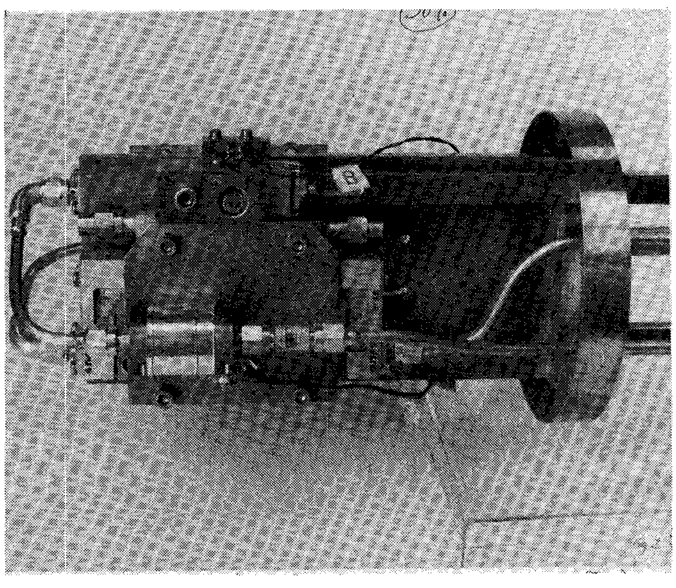

Fig. 2. Parametric amplifiers mounted on the copper heat sink (can cover removed). The first stage amplifier is behind the heat sink.

taken to seal the can and only small changes were observed in the amplifier gain, bandwidth, and pump power requirements as the assembly was cooled to 4.2 K.

Input and output signals were coupled to the paramps through 0.141-in-diameter stainless steel coaxial lines. These lines had a ~2-dB loss at 4750 MHz. A 30-dB attenuator (Weinschel Model 3M-30) was connected to the paramp input via a short section of stainless coax (loss 0.4 dB). The pad served to isolate the paramps from room-temperature input noise and to minimize the effects of VSWR changes in either the paramp or noise diode (ND) calibration source. The loss and VSWR of the attenuator were measured both at 295 K and 4.2 K, and were found to differ only slightly at the two temperatures; loss changed by <0.5 dB, and VSWR increased from 1.05:1 to 1.15:1 at the lower temperature.

The 30-dB attenuator was also used to calibrate the equivalent noise temperature of the external ND source at the paramp input. The attenuator was enclosed in a copper cylinder with a heater coil wound around its exterior. A temperature sensor was mounted on the inner surface of the cylinder next to the attenuator body to measure the temperature of the attenuator.

ND calibration was done by using the heated attenuator as a hot/cold load between 4.2 K and 6 K, and by measuring the system noise. Because heat capacities are low at 4 K, the attenuator temperature stabilized within a few seconds after the heater was switched on or off, and the change in the detector output voltage could be easily measured. After a cycle of noise measurements was made using the heated attenuator, the ND was switched on, and total system noise measured again using the Y-factor method. Knowing the temperature of the heated attenuator then allowed the ND's equivalent noise temperature at the paramp input to be calculated. The only assumption made here is that system noise remains constant over the few seconds required to make both measurements. ND calibrations were made at frequent intervals over the four-month period covered by this experiment, and results were found to be highly reproducible. A value of 555 ± 55 K was obtained for the equivalent noise temperature of the diode referred to the paramp input at 4750 MHz, with the diode mounted directly on the input coax line. (The error represents the maximum estimated error.)

Once calibrated, the ND was simple and quick to use and was employed at ambient temperatures above 4.2 K, where large heat capacities and thermal transport effects make use of the heated attenuator impractical; the ND was therefore used for the majority of the noise measurements. Because it was necessary to reduce systematic errors in the calibration, a second independent method was used to calibrate the diode. This was done by directly measuring the temperature of the ND source and the input loss to the paramp when the assembly was cooled to 82 K and 4.2 K. The ND temperature was measured by comparing the temperature of the ND padded with a 30.20-dB precision attenuator to an AIL Hot/Cold Standard Calibration Source (Model 70). The ND was measured to have an excess noise ratio (ENR) of 35.08 ± 0.1 dB at 4750 MHz. The loss of the input line to the paramp was determined by measuring the attenuation of just the input and output stainless steel coax lines (1.96 dB each at 4750 MHz) and then measuring the total loss with the 30-dB Weinschel attenuator and a short jumper. These measurements were done both at 82 K and 4.2 K and the loss to the paramp was calculated. Results are given in

TABLE II
CALIBRATION VALUES

Frequency (MHz)	T_a (K)	Loss to Paramp Input (dB)	T_H = Noise Diode Calibration Temp. (K)	3rd Stage Noise Temp. (K)	Unpumped Paramp Loss (dB)
4750	82 K	32.32 ± 0.1	629.7 ± 15	1000 ± 20	1.34 ± 0.1
4750	4.2 K	32.36 ± 0.1	547.0 ± 13	903 ± 20	1.74 ± 0.1
4160	4.2 K	32.34 ± 0.1	531.3 ± 12	808 ± 20	2.21 ± 0.1

Errors represent measurement scatter and do not include systematic effects.

Table II. In the measurement of this large attenuation, the test signal was referenced to the same 30.20-dB precision attenuator used in the ND calibration. Thus only small differences had to be measured and errors in these measurements due to errors in the 30.20-dB attenuator tend to cancel in the calculation of the calibration temperature.

The 30-dB attenuator at the paramp input reduces the temperature contribution from the input coax to negligible values, and the ND calibration temperature is then given by

$$T_H = T_L + \frac{T_{ND}}{L_{in}}$$

where

T_L temperature of the 30-dB attenuator
T_{ND} temperature of the ND
L_{in} input loss to the paramp.

Calculated values of the ND calibration temperature with the ND directly on the input are shown in Table II. Note that the 4750-MHz value is in excellent agreement with the value determined using the heated attenuator method described above.

As shown in Fig. 1, the output signal from the paramps is carried by a stainless steel coaxial line to a room-temperature circulator with a cooled termination. The circulator provides good matching and reduces the noise reflected back into the paramps. The circulator is followed by a 4- –8-GHz GaAs FET amplifier with a 3.5-dB noise figure and 40 dB of gain. A small portion of the FET amplifier output is sampled for bandpass display. Following the FET amplifier, the signal is mixed down to 30 MHz, passed through a 10-MHz-wide bandpass filter, and passed through a precision attenuator (AIL Model 30); it is then further amplified and sent to a crystal detector whose output voltage is measured by a digital voltmeter. The noise temperature of this third stage noise measurement system is listed in Table II. This was measured using the ND calibration source during the determination of the total line loss, as described above. The noise measurement receiver could be tuned through the range 4.0–5.5 GHz, by tuning the LO signal generator; however, most measurements were made with the LO at 4750 MHz, with a few at 4160 MHz as discussed below. Noise signals from both sidebands, ±30 MHz around the LO were measured.

TABLE III
PARAMP NOISE TEMPERATURE MEASUREMENTS

Frequency (MHz)	T_a (K)	T_{sys} (K)	Gain 1 (dB)	Gain 2 (dB)	T_{paramp} (K)
4750	4.2	17.1 ± 1.7	11.8	11.5	12.1 ± 2.2
4750	18	21.8 ± 2.2	12.8	12.4	18.1 ± 3.5
4750	82	46. ± 5.	12.7	11.7	40.5 ± 7.3
4160	4.2	12.7 ± 1.3	14.0	8.5	7.3 ± 1.3

± Errors represent the best estimate of the maximum errors.

To accurately calculate the paramp noise temperatures, it is important to know the paramp gain within ±0.3 dB. This was accomplished by tuning the sweep/signal generator to the center frequency and modulating it at 1 kHz. A SWR meter was then used to measure the output of the first detector. Each paramp stage was turned off in succession to measure its "total electronic gain" to within ±0.2 dB. The loss through the unpumped paramps at 4.2 K and 82 K was determined by measuring the loss through the assembly with and without the paramps in place. These values are also listed in Table II, and were subtracted from the total gain values to determine the true gain of each stage.

III. RESULTS

Measurement results are listed in Table III. These values represent typical measurements at the ambient temperatures tabulated. The data taken at 18 K represent measurements made as the paramps were warming up —this accounts for their larger scatter. In calculating paramp noise temperature T_{paramp}, it was assumed that the noise temperature of each stage was the same. In one measurement only a single stage was used, and the value derived for T_{paramp} was 10±3 K. This is consistent with the other values given in Table I, supporting the equal noise assumption. (The large error in this value is due to uncertainties in the large correction for the second stage contribution.)

At 4750 MHz, paramp noise temperature decreased from 18 K to 12 K as the paramps were cooled from T_a = 18 K to 4.2 K. This suggests that if the production amplifiers had been used, yielding the specified noise temperature of 15 K at T_a = 18 K, a noise temperature of ~9 K would have been obtained at T_a = 4.2 K. As discussed in the next section, this performance could be further improved by using varactors requiring less pump power and having lower thermal resistance.

The noise temperatures shown in Table III represent minimum values with respect to gain, i.e., as gain was increased by using more pump power, noise temperature also increased slightly. This supports our conclusion that varactor heating is responsible for the higher than expected noise temperatures, as discussed in Section IV.

The final entry in Table III is for a lower frequency narrow-band (~70 MHz) paramp mode centered at 4160 MHz. The amplifiers were easily tuned to this state by reducing varactor bias and pump power. The very low (~7 K) noise temperature obtained in this mode appears to be related to the ~2-dB reduction in required pump power (cf. Section IV).

IV. Discussion

These measurements demonstrate that a commercially available paramp can be operated at 4.2 K, and that amplifier noise temperature decreases by 6 K on cooling from $T_a = 18$ K to 4.2 K. Using production units, it may be possible to obtain a 9 K paramp, one of the lowest noise amplifiers available today.

The major question raised by our measurements is why the drop in ambient temperature by a factor of four did not produce a similar drop in noise temperature. A previous measurement of a parametric amplifier at 4.2 K also indicated excess noise, but no satisfactory explanation could be found [6]. Based on the measurements of circulator loss (which did not change significantly between $T_a =$ 80 K and 4.2 K) we conclude that varactor heating is the main cause of the higher than expected noise temperature. This can be illustrated with the following expression for paramp noise temperature [7], [8].

$$T_{\text{paramp}} = T_a\left(1 - \frac{1}{L_c}\right) + L_c(T_a + \Delta T)\left[\frac{f_s}{f_i} + \frac{1 + f_i/f_s}{\tilde{Q}^2 - f_i/f_s}\right]. \tag{1}$$

Here

- T_a ambient temperature
- L_c loss of input circulators ($\cong 0.7$ dB)
- ΔT temperature rise of varactor diode due to pump heating $= R_{\text{th}} P_D$
  - R_{th} thermal resistance of varactor
  - P_D pump power absorbed by the varactor
- f_s signal frequency ($=4750$ MHz)
- f_i idler frequency ($=21\,550$ MHz)
- $\tilde{Q}$ dynamic Q factor $= \dfrac{\gamma f_{ce}}{f_s\sqrt{1 + r_i/r_s}} = \dfrac{\gamma}{2\pi f_s \bar{C}\sqrt{r_s(r_s + r_i)}}$
  - f_{ce} cutoff frequency at bias ($\cong 143$ GHz)
  - γ modulation coefficient ($\cong 0.22$) for the fully pumped diffused junction varactor
  - $\bar{C}$ average value of junction capacitance at -0.8-V bias ($\cong 0.19$ pF)
  - r_s spreading resistance ($\approx 6\ \Omega$)
  - r_i equivalent idler resistance ($\approx 4.5\ \Omega$).

Using the preceding values, the value of $\tilde{Q}$ is calculated to be $\tilde{Q} = 5$.

Estimating varactor temperature rise is more difficult. We have measured that ~40 mW was absorbed by each paramp stage. Some of this power is absorbed in the varactor mount, and the rest by the diodes. (This is a balanced two-varactor mount so the power is divided between the two diodes.)

The theoretical expression for the pump power required for a fully pumped graded junction varactor is [9]

$$P_d = 0.27\left(\frac{f_p}{f_{cp}}\right)^2 \frac{V_p^2}{r_s} = 0.27 f_p^2 V_p^2 (2\pi C_{\min})^2 r_s \tag{2}$$

where

- f_p pump frequency ($=26.3$ GHz)
- f_{cp} cutoff frequency measured at pump frequency (≈ 200 GHz)
- V_p peak-to-peak varactor voltage (≈ 2.6 V)
- $C_{\min}$ minimum junction capacitance (≈ 0.15 pF).

Experience has shown that actual pump power requirements will be ≈ 6 dB larger than this minimum value [10], [11], and thus substituting in the nominal values with this correction yields $P_d = 26$ mW. This is twice the power required per diode in this balanced mount, resulting in a power of ≈ 13 mW/diode.

The thermal resistance provided by the varactor manufacturer for this diode is $R_{\text{th}} = 200$ K/W at $T_a = 300$ K. Holland [12] has found that R_{th} of GaAs decreases by ≈ 30 from 300 K to 18 K, but then increases by ≈ 5 at 4.2 K. However, Weinreb (private communication) has determined that at 4.2 K, the size and shape of the GaAs sample greatly influences R_{th} for small diodes, and that R_{th} is often much higher than predicted. Thus the value of R_{th} at 4.2 K is very uncertain.

Holland's data predict that $R_{\text{th}} = 33$ K/W at $T_a = 4.2$ K. This would produce a diode temperature rise of $\Delta T =$ 0.4 K, and using (1) with $T_a = 4.2$ K and $\tilde{Q} = 5$ then yields $T_{\text{paramp}} = 3.3$ K. This is ≈ 10 K lower than the calculated noise temperature at $T_a = 18$ K and in disagreement with the 6 K measured difference.

Two possible reasons for this discrepancy are an increase in the diode's series resistance at $T_a = 4.2$ K, and/or a larger than nominal varactor thermal resistance. Dominick [13] has studied varactor series resistance at different temperatures and found little change from room temperature to 20 K; however, increases in r_s by factors of 0.8 to 6.0 were noted as the diodes were cooled from 20 K to 4.2 K. Data for the diffused pn-junction epitaxial GaAs varactors with mesa construction, used in the AIL paramps (Frequency Sources, GHz Division, No. GC-5512B, $C_{j0} = 0.23$ pF, $V_b = 10$ V) are not available, but it is reasonable to expect some increase in r_s as the diodes are cooled from $T_a = 18$ K to 4.2 K. However, it is noted from (2) that pump power is proportional to r_s. Since the required pump power (for the same gain and bandwidth) was observed to *decrease* slightly (~0.6 dB) as the paramps were cooled from 80 to 4.2 K, this implies that r_s

did not change significantly as the temperature was reduced.

This fact then brings into question the estimate of R_{th} used above. A much higher value is required for agreement with the measured data. A value $R_{th}=600$ K/W at $T_a=4.2$ K gives $T_{paramp}=7.5$ K, and using $R_{th}=7$ K/W for $T_a=18$ K, based on the manufacturer's data and the R_{th} reduction determined by Holland [12], one calculates $T_{paramp}=13.1$ K. This predicted difference of 5.6 K is in reasonable agreement with the present measurements. Thus it is concluded that a large diode thermal resistance is required to explain the higher than expected noise temperatures measures at 4.2 K. Weinreb (private communication) has measured similarly large values of R_{th} in his work on parametric downconverters using GaAs varactors.

Additional confirmation of this conclusion is given by the results at 4160 MHz, where a lower noise temperature was measured with $\sim$2-dB less pump power. The 2-dB lower pump power implies a 1.6 decrease in r_s and thus a 1.6 increase in $\tilde{Q}$ and a 1.6 decrease in ΔT. Substituting these values in (1) leads to a $T_{paramp}=4.3$ K, which is $\approx$3 K lower than the 4750-MHz value and is in reasonable agreement with the $\sim$5 K difference which was measured.

These results and their first-order agreement with theoretical predictions suggest interesting possibilities for the development of very low noise amplifiers. Since the increase in thermal resistance as T_a is lowered to 4.2 K is intrinsic to GaAs, development goals should be to reduce R_{th} and the pump power required by the varactors. Schottky barrier diodes having cutoff frequencies twice that of the diodes used here have recently been developed. Consequently, these varactors would require less pump power and, in addition, may possess significantly lower R_{th} due to their metalized construction [14]. Designing a parametric amplifier with such diodes to operate at helium temperatures should yield an amplifier with a noise temperature of $\sim$5 K.

Another interesting question which was briefly explored in this research was the behavior of the paramps at temperatures below 4.2 K. During one of the measurements, the dewar vacuum line was opened and reduced pressure lowered the paramp temperature to 1.7 K. The paramps continued to operate properly with respect to gain and bandpass, and a measurement of noise temperature showed that it had increased by 2 K from the $T_a=4.2$K value. This is not consistent with the expected increase of R_{th} at 1.7 K; however, superfluid helium surrounded the paramp during this measurements, which may have dramatically decreased the thermal resistance of the varactor.

References

[1] A. R. Kerr, "Low-noise room-temperature and cryogenic mixers for 80–120 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 781–787, Oct. 1975.

[2] R. A. Linke, M. V. Schneider, and A. Y. Cho, "Cryogenic millimeter-wave receiver using molecular beam epitaxy diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 935–938, Dec. 1978.

[3] F. L. Vernon, Jr., M. F. Millea, M. F. Bottjer, A. H. Silver, R. J. Pedersen, and M. McColl, "The super-Schottky diode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 286–294, Apr. 1977.

[4] S. Weinreb, "Millimeter wave varactor down converters," presented at the Diode Mixers at Millimeter Wavelengths Workshop, sponsored by Max Planck Institut for Radioastronomie (Bonn, W. Germany, Apr. 26–28, 1977).

[5] G. J. Dolan, T. G. Phillips, and D. P. Woody, "Low noise 115 GHz mixing in superconducting oxide barrier tunnel junctions," *App. Phys. Lett.* (in press), 1979.

[6] P. A. Watson, "The noise temperature of liquid helium cooled parametric amplifiers," in *Proc. Phys. Aspects of Noise in Electron. Devices Conf.*, 1968, Univ. of Nottingham, England, Sept. 11–13, 1968, pp. 243–248.

[7] K. Garbrecht, "Lower limit of paramp noise due to pump heating," in *1965 Int. Solid-State Circuits Conf. Dig.*, Philadelphia PA, pp. 22–23, Feb. 1965.

[8] J. Edrich, "Parametric amplifiers," in *Methods of Experimental Physics*, vol. 2, pt. B, sect. 3.2, M. L. Meeks, Ed. New York: Academic, 1976.

[9] P. Penfield and R. P. Rafuse, *Varactor Applications*. Cambridge, MA: M.I.T. Press, 1962, ch. 7.

[10] G. Sard, A.I.L., private communication.

[11] P. J. Moogk and U. Rutulis, "Six formulas simplify paramp design," *Microwaves*, vol. 5, pp. 36–41, May 1966.

[12] M. G. Holland, "Phonon scattering in semiconductors from thermal conductivity studies," *Phys. Rev.*, vol. 134, pp. A471–A480, 1964.

[13] F. J. Dominick, "Cooled and uncooled varactors for paramp applications," Lincoln Lab. Tech. Note 1966-27, 1966.

[14] J. A. Calviello and J. L. Wallace, "Performance and reliability of an improved high-temperature GaAs Schottky junction and native-oxide passivation," *IEEE Trans. Electron Dev.*, vol. ED-24, pp. 698–704, June 1977.