Characterization of a complementary metal-oxide semiconductor operational amplifier from 300 to 4.2 K

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We report the first operation of a commercially available complementary metal-oxide semiconductor operational amplifier, at liquid helium temperature. In addition, we have characterized several factors important to the practical application of such a circuit from room temperature down to 4.2 K. The temperature dependence and measurement techniques for open-loop gain, input offset voltage, input referred noise voltage, and quiescent current are presented. We will discuss our observations of low temperature behavior of the opamp with respect to others' previous results. This work represents an advancement over earlier studies which only reported opamp operation down to 77 or 30 K with measurements taken only at a limited number of temperatures instead of a broad range. Our data suggest that under special operating conditions the opamps can be effectively used with careful consideration of noise and gain performance. Input offset voltage levels and quiescent current (including power consumption) resemble normal room temperature operation. © *1995 American Institute of Physics.*

I. INTRODUCTION

In cryogenics, it is unavoidable to use long wires to connect a sensor deep inside a dewar to external equipment. Any significant amount of electrostatic coupling between these wires can degrade the signal quality, especially for high impedance measurements. A large sensor resistance can easily cause the RC time constant to be unacceptably large, even for a moderate value of coupling capacitance, and hence reduce the possible sampling rate. The stray capacitance also introduces unwanted electromagnetic pickup noise and makes precision measurement difficult. As a result it is necessary to install the preamplifier as close to the sensor as possible to minimize these capacitive coupling effects.[1]

There have been numerous studies of the performance of electronic components at liquid helium temperature.[2] In general, bipolar transistors fail to operate at such low temperatures because of the drastic drop in carrier density.[3] Although studies have been done on junction field-effect transistors,[4,5] the transistor device that has been commonly used at 4.2 K is the metal-oxide-semiconductor-field effect transistor (MOSFET).[6] It has been demonstrated that Si type can be operated at low temperatures,[7,8] with a slower time response. It is necessary for the channel to remain conducting in order for the MOSFET to function properly, and it is quite possible for the channel temperatures to be considerably higher than 4.2 K and prevent complete carrier freeze-out.[5]

Most of the applications of MOSFETs at low temperatures are limited to simple circuitry such as a follower, or simple amplifier. This severely limits the use of electronics at very low temperatures; in addition, there are no commercial integrated circuits specially designed for this purpose. Commonly available integrated circuits will fail to properly operate at 4.2 K because they have bipolar transistor components. Previous studies have investigated commercially available operational amplifier (opamp) performance at temperatures as low as 77 K (Refs. 9 and 10) and 50 K.[11] In one of the reports it was shown that a certain opamp could be operated at 30 K, but would not perform properly at 20 K.[11] In any case, opamps are most likely to be used in measurements at liquid helium temperature (4.2 K). In this paper, we will demonstrate the first operation of a commercially available opamp at 4.2 K. Further, we have characterized the opamps in terms of open-loop gain, input offset voltage, input referred noise voltage, and quiescent current over a temperature range from 300 to 4.2 K. We will report the temperature dependence of these characteristics and interpret the phenomenon we have observed. In the end we will also discuss the advantages and limitations of using an all MOSFET opamp at a broad range of cryogenic temperatures and specifically at liquid helium temperature. This will allow a large variety of electronic circuits to be applied to low temperature measurements.

One example that we have used is a current to voltage converter for low temperature scanning tunneling microscopy. To avoid crashing between the tip and sample, the tunneling junction resistance must be kept in the order of 10 to 100 MΩ. The large junction resistance is also essential to minimize the current density, and hence reduce the current depairing effect for tunneling between semiconductors. With a ramping bias of ± 10 mV, the corresponding tunneling current is only about 100 pA. Such a small signal is very difficult to measure from a large resistance source, because of the pickup noise. Also, a minimal stray capacitance of 1 nF will cause an unacceptably large time constant for the high data acquisition rate of a scanning tunneling microscope (STM). We have constructed a simple current to voltage converter circuit close to the STM with the opamp we discuss below, the data taking rate (I-V measurement) is increased by four to five times and the noise level is also significantly improved. However, the heat generated by the opamp increases the operating temperature to about 9 K because both the STM and the opamp are not in direct thermal contact with the liquid helium bath.

Opamps that can be operated at 4.2 K must be all MOSFET. Most of the opamps available (including FET input opamps) have some bipolar transistor stages in the circuit. We have tested many of these opamps, and none of them can be operated in a liquid helium environment. The only all MOSFET opamp we have tested so far is Harris Semiconductors' ICL7611. We have determined that ICL7611 can function properly at liquid helium temperature, under special operating procedures. These procedures include the use of bias voltages of up to ±13 V below 50 K in order to maintain operation. While operating an opamp so far outside of its rated supply voltage may seem to be a serious problem, it must be considered that this voltage is only applied at temperatures below 77 K. Since most failure mechanisms are thermally activated, the lower temperature allows safe operation above the standard voltage ranges. In fact, we have never experienced a failure as a result of using ±13 V at 77 K or lower.

II. EXPERIMENTAL SETUP

The ICL7611-DMTV operational amplifiers's open-loop gain, input offset voltage, input referred noise voltage, and quiescent current were characterized from 300 to 4.2 K. Each test required a different configuration of the opamp, but in general the opamp was mounted on the end of a stainless steel probe with all connecting wires twisted together inside the probe's hollow tube. The probe was slowly lowered into a dewar containing liquid helium while temperatures were monitored with a Lakeshore Cryotronics DT-470-SD-13 diode sensor. The sensor was attached directly to the opamp's case, so all temperatures are actual device package temperatures. Above 50 K the supply voltages were maintained at ±7.5 V; between 50 and 4 K the supply voltages were increased to ±13 V. In all cases the quiescent current was set high to 1 mA.

To measure the open-loop gain a small sine wave signal was applied to the noninverting input of the opamp through a 100 to 1 voltage divider while the inverting input was connected to ground. The amplitude of the input signal had to be chosen carefully in order to prevent clipping at the opamp's outputs. The opamp's internal offset nulling capability was used to maintain an approximate zero offset throughout the measurements. Unlike the other tests the opamp's output was connected by a wire outside the probe's tube to prevent undesirable oscillations due to input–output coupling. However, this coupling did not present a problem in the closed-loop configuration. Besides monitoring the output signal with an oscilloscope, a computer controlled Stanford Research SR770 fast Fourier transform Spectrum Analyzer was used to measure the peak to peak output voltage at the exact frequency of the input signal, and the open-loop gain was given by the ratio of the output to input signal levels.

The input offset voltage was measured by placing the opamp in a noninverting closed-loop configuration with a gain of approximately 11 and with the offset nulling capability disconnected. An appropriate input signal was applied to the noninverting input and the inverting input was connected to ground. To obtain the actual input offset voltage the dc output voltage was measured with respect to temperature and divided by the exact gain at that temperature.[12] This was necessary because the feedback resistance increased as the circuit cooled.

The input referred noise voltage was measured at approximately 10° intervals from 300 to 4.2 K with a slightly higher data concentration in the region from 10 to 40 K because of that region's unusual noise behavior. The amplifier was configured in the same manner as for the input offset voltage test, but the inputs were both shorted to ground and the output was monitored on the SR770 Spectrum Analyzer from 0 Hz to 100 kHz.[12] The analyzer measures power spectral density normalized to a 1 Hz bandwidth; thus, the noise level can be read directly in $V_{rms}/Hz^{1/2}$. Data was taken in 250 Hz increments across this range after the opamp's temperature stabilized, and the value was divided by the gain at that temperature.

Finally the opamp's quiescent current was measured against temperature. The opamp was configured as a closed-loop noninverting amplifier, and a computer controlled multimeter was inserted into the circuit at the positive supply connection to monitor the current. The opamp was slowly cooled to 4.2 K with the standard supply voltage shift from ±7.5 to ±13 V at 50 K. All of these tests were performed on multiple opamps and the results given are those of typical samples.

III. DISCUSSION AND ANALYSIS

It is important for us to understand why the opamp can operate at liquid helium temperature before its low temperature performance can be evaluated properly. At 4.2 K it is clear the carrier freeze-out is complete and that the MOSFET's channel is an insulator.[13] According to earlier studies, the channel can be kept conducting by two mechanisms. The first is localized heating. It has been shown that the actual channel temperature of a MOSFET can be tens of degrees higher than the ambient temperature at 4.2 K. If this is the case carrier freeze-out would not be complete and the channel would remain conducting.[5] This may provide an easy explanation for the required increase in supply voltage. The increased voltage and current leads to a greater power dissipation and higher channel temperature. However, this does not fully explain the phenomenon because the device can be switched on immediately after long periods of inactivity at low temperatures. If localized heating is the only mechanism to maintain channel conductivity, it is not possible to reactivate the opamp after the channel is frozen. The lack of a "warm up" period requires additional mechanisms for channel conduction.

A previous study has demonstrated the existence of a conducting layer above the frozen-out substrate. At low temperatures, the free carriers in the conducting layer can be created by field ionization of the impurities close to the electrodes.[13] Further, for a device which lacks gate to source and gate to drain overlap, the drain to source voltage must be greater than a certain threshold voltage for the conducting layer to form.[14] This threshold voltage requires an increase in

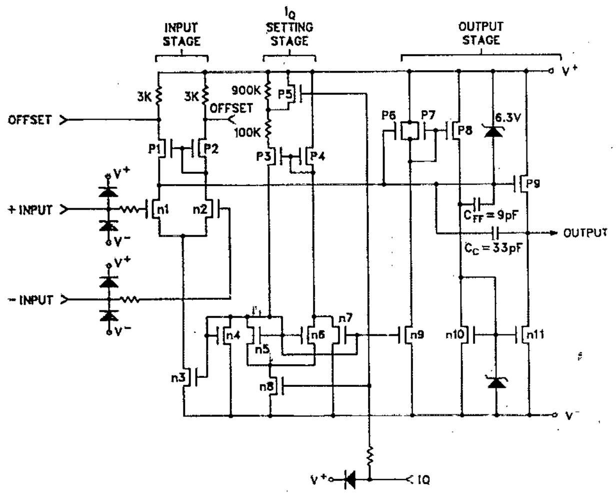

FIG. 1. Functional diagram for the ICL7611-DMTV opamp. N-channel MOSFETs are designated as nX and p-channel as PX.

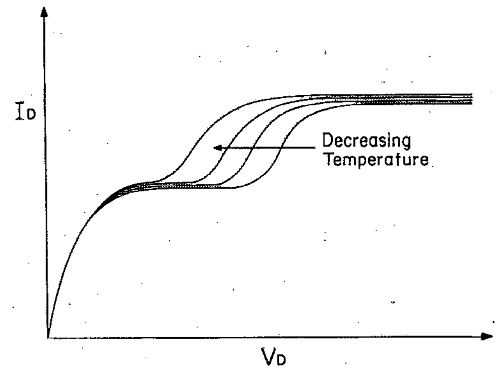

FIG. 2. The current kink in the MOSFET I-V curve at low temperatures is schematically shown here. Note that the critical voltage decreases with decreasing temperature. (Adapted from Ref. 21.)

supply voltages for the operation of the opamp after the channel is frozen-out. We want to point out that it is a trend to reduce the gate to source and gate to drain overlap for higher speed devices. Hence, increasing supply voltage is an unavoidable step in using commercial opamps at low temperatures. Once current is flowing in the conducting layer, local heating takes over to free more carriers and opens up the channel[15] for normal operation of the opamp. Here we are presenting some of the low temperature characterization results that readers may find useful. Throughout this discussion we will refer to the specific MOSFETs in Fig. 1, the functional diagram of the ICL7611 opamp.[16]

The formation of the conducting layer dramatically changes the characteristics of the opamp in the temperature range of 10–40 K, until the conducting layer becomes stable at very low temperature (less than 10 K). This phenomenon is a consequence of the current kink effect in a single MOSFET device at low temperatures that has been observed by other researchers.[11,21] It has been noted that when a MOSFET is at low temperatures, provided it is still conducting, the channel current I_D will increase with the channel voltage V_{DS} (gate voltage is kept constant) until a certain critical voltage (the kink voltage) of several volts. At this critical voltage the channel current experiences a sudden increase as schematically shown in Fig. 2. Balestra *et al.*[21] suggested the possibility of a weak avalanche near the drain space charge region (for n-channel MOSFET) that leads to the current kink. An avalanche occurs because the conducting layer is isolated from the substrate contact by the frozen bulk of the substrate and the greatest part of I_D must flow through the conducting layer into the source. As the temperature is reduced, the conducting layer becomes more and more isolated from the substrate contact and more current flows into the source. As a result, the kink voltage drops as the temperature is lowered (Fig. 2). The sensitivity of this process to temperature causes irregularity in the behavior of the opamp until very low temperatures at which the channel is completely isolated from the substrate contact. One example is the noise level of the opamp, which becomes anomalously high between 10 and 40 K and then goes back to normal level at temperatures below 10 K.

The input referred noise level of an operational amplifier is critical to its application and is also temperature dependent. The primary source of noise in a MOSFET opamp is frequency-dependent flicker noise in the input stages. One approximation for the overall noise of the opamp is given by[19]

$$\epsilon^n = \left[V_{n1}^2 + V_{n2}^2 + \left(\frac{g_{P2}}{g_{n1}} \right)^2 (V_{P1}^2 + V_{P2}^2) \right]^{1/2},$$

where V_{n1}^2, V_{n2}^2, V_{P1}^2, and V_{P2}^2 are equivalent rms input noise voltages of MOSFETs $n1$, $n2$, $P1$, and $P2$. The transconductances of $P2$ and $n1$ are given by g_{P2} and g_{n1}. As can be seen from this equation the noise level of the opamp is heavily influenced by the input MOSFETs which are n-channel devices. Each transistor displays noise which is inversely proportional to frequency, and although there is no definite explanation for flicker noise some generalizations can be made. Flicker noise is mainly a result of the trapping and release of carriers on the Si surface. The timing of this process concentrates the noise in lower frequencies. As a MOSFET is cooled trapping becomes more pronounced and the noise level increases. There are also elements of Johnson (thermal) and shot noise, but flicker noise remains the dominant noise source over the frequencies we tested.

Figure 3 shows the input referred noise voltage plotted against frequency at 300, 77, and 4.2 K. The noise voltage is $1/f^a$ in nature with f representing frequency and a varying

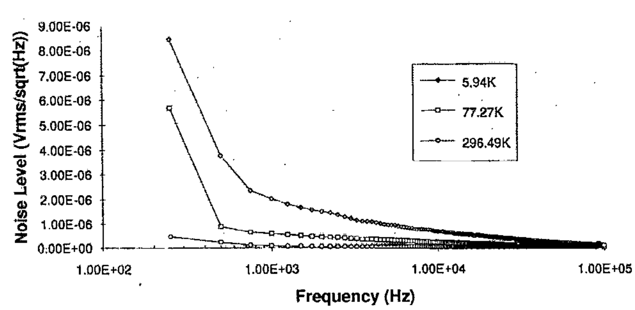

FIG. 3. Input referred noise voltage vs frequency at 300, 77, and 4.2 K.

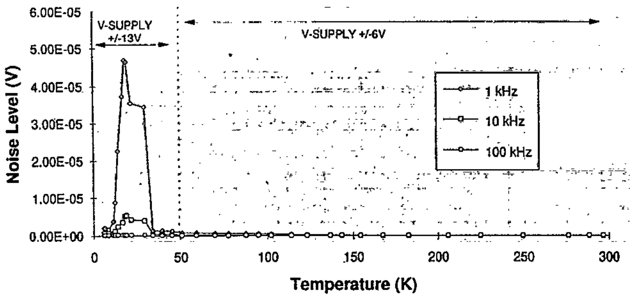

FIG. 4. Input referred noise voltage vs temperature at 1, 10, and 100 kHz. Note the drastic increase in noise between 10 and 40 K.

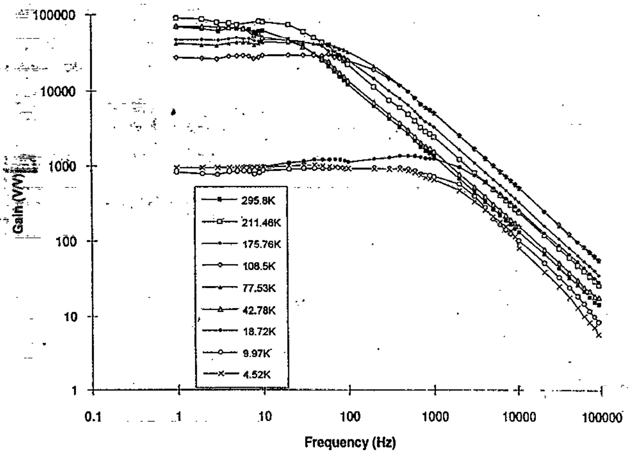

FIG. 6. Open-loop gain of a typical opamp with respect to frequency at varying temperature between 300 and 4 K. Note the consistency of the high frequency open-loop gain.

from 0.9 to 1.3 depending on temperature. The noise level increases with decreasing temperature which is typical of n-channel MOSFETs and opamps with n-channel inputs such as the ICL7611.[17] The opamp noise level is specified at room temperature to be less than 100 nV/Hz$^{1/2}$ at 1 kHz.[16] In our tests the opamps remained within these specifications above 65 K. Figure 4 shows the overall temperature dependence of the noise voltages at 1, 10, and 100 kHz.

In all the opamps tested there was a large increase in noise between 10 and 40 K which peaked at about 1 mV$_{rms}$/Hz$^{1/2}$ for 1 kHz. This can be partially explained by the existence of a current kink in this region. As discussed below we believe the extra noise in this temperature range is due to the instability of the newly formed conduction layer by the field ionization mechanism. This is consistent with the observation that one of the symptoms of current kinking is a sharp increase in noise.[21] After the conducting layer stabilizes at about 10 K, the noise decreased rapidly to 2.01 μV/Hz$^{1/2}$ at 4.2 K. However, this is still considerably higher than the noise level at room temperature.

The quiescent current of the opamp is roughly equal to the sum of all channel currents within the integrated circuit and it varies considerably with temperature. As can be seen in Fig. 5 there is an initial increase from 1.5 to 9 mA between 300 and 130 K. As the transistors are cooled phonon scattering decreases; as a result, carrier mobility increases and a greater current is allowed to flow in the channel. At the 130 K current peak phonon scattering ceases to be the dominant mechanism controlling the channel current and carrier freeze-out begins to reduce the number of available carriers and thus the current.[18] Following this the current decreases down to 77 K with a slight, but reproducible, kink around 100 K. At 77 K the supply voltage was increased to ± 13 V and the decrease continued down to 50 K. Between 50 and 20 K the opamp displayed two sharp current jumps followed by level regions. Finally, the current dropped off to about 3 mA at 4.2 K. This value gives an estimated power dissipation of 78 mW (corresponding to a liquid helium boiling rate of 0.1 ℓ/h). The opamp has to be thermally anchored to the liquid helium bath for low temperature applications. It is also interesting to note that the abnormal current behavior corresponds to the region of increased noise. The jumps in the current reflect the formation of the conducting layer in the MOSFET. There are several jumps because of different types of MOSFET in the opamp.

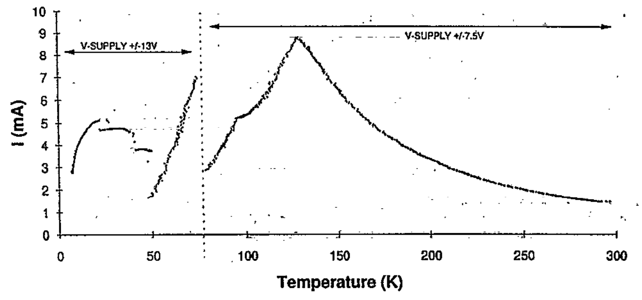

FIG. 5. Quiescent current of a typical opamp as measured at the positive supply with respect to temperature.

The open-loop gain of an opamp is determined by the ratio of the change in output voltage to the change in input voltage at a certain frequency when there is no feedback connected. The ICL7611 with supply voltage at ± 7.5 V and I_Q at 1 mA has a typical low frequency open-loop gain of approximately 90 000, with a rolloff beginning at approximately 10 Hz.[16] Figure 6 shows the open-loop gain of the opamp with respect to frequency at various temperatures. Between 300 and 40 K the gain fluctuates slightly; in addition, one notices a decrease in low frequency open-loop gain at temperatures below 10 K. The noise present in the opamp between 20 and 40 K overloaded the outputs and the open-loop gain could not be determined. It is interesting to point out that when the open-loop gain was measured at 77 K (Fig. 7), it progressively decreased with increasing supply voltage. When measurements were taken at 42 K with a ± 13 V supply the open-loop gain returned to the room temperature value. This indicates that the open-loop gain is dependent on both temperature and supply voltage. According to other reports,[11,13,20] 77 K is too high for field ionization to occur. Hence, the effects of temperature and supply voltage should be carefully distinguished. The reduction in gain with increasing supply voltage at 77 K is simply due to the regular behavior of the MOSFET, namely, channel conductance rises and transconductance falls as V_{DS} increases (see the equation below).

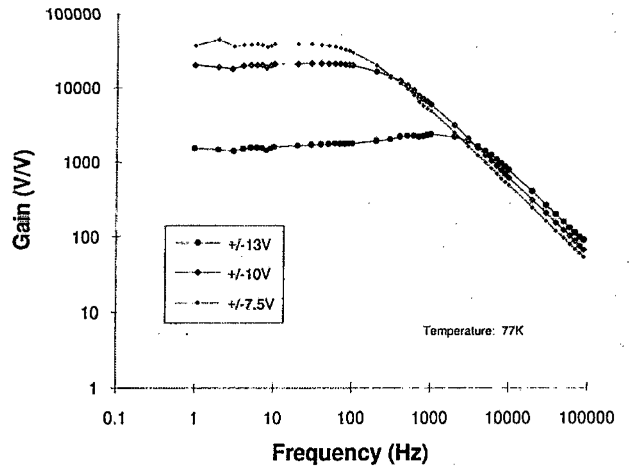

FIG. 7. Open-loop gain of a typical opamp at 77 K at supply voltages of ±7.5, ±10, and ±13 V.

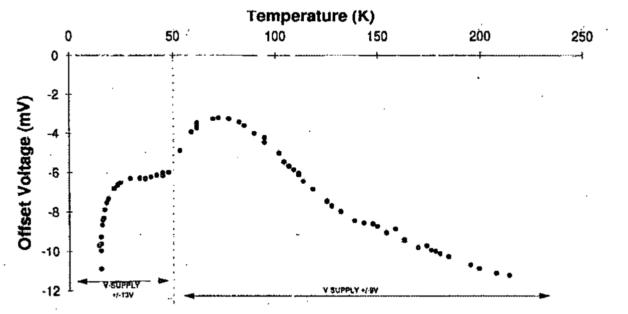

FIG. 8. Input offset voltage plotted against temperature with the offset nulling capability disconnected. The specification for normal temperatures is 20 mV.

The low frequency open-loop gain for this opamp is approximated by

$$A_{\mathrm{OL}}=(g_{m_{n1}}G_{m_{n9}})/(g_{0_{n2}}+g_{0_{P2}})(g_{0_{P9}}+g_{0_{n11}}),$$

where g_m terms represent the transconductance and g_0 terms represent the channel conductance of the designated transistor. The transconductance of an individual transistor is proportional to $I_D^{1/2}$, while the channel conductance is proportional to I_D.[19] Therefore, the open-loop gain for the opamp is proportional to I_D^{-1}, but g_m and g_0 also vary inversely with temperature.[5] This means that the increasing transconductance pushes the gain up, while the increasing channel conductance pulls it down. All the while, the gain is being adjusted in accordance with the changing current. Therefore, open-loop gain does not vary inversely with the quiescent current of the opamp or with the temperature as the device is cooled. Instead, it fluctuates in a manner which can only be qualitatively explained.

In the region below 40 K there is a disproportionate decrease in open-loop gain which cannot be explained by standard shifts in transconductance and channel conductance. However, we have previously demonstrated that the open-loop gain is sufficient for most practical applications from room temperature to 4.2 K.[20] Balestra *et al.* have shown that operating a MOSFET at or above the critical drain to source voltage for a current kink is accompanied by a sharp increase in channel conductance.[21] As seen in the equation above a rapid increase in channel conductance would yield a decrease in open-loop gain. The drop in gain happens around the temperature range in which Balestra noticed the occurrence of current kinks, approximately 30 K. At low temperatures, the MOSFETs are actually operating in the "kink" region which has a channel conductance orders of magnitude higher than the saturation region (Fig. 2). At 42 K, the high supply voltage of ±13 V is still large enough to keep the MOSFETs in the opamp functioning normally above the kink region. As the temperature is cooled down, the kink effect starts to occur and the characteristics of the MOSFETs are very sensitive to temperature changes. This gives rise to many undesirable effects, such as abrupt increase in noises and sudden jumps in quiescent currents, of the opamp. Some of these undesirable effects will disappear as the characteristic curve becomes stable at very low temperatures (below 10 K). However, the MOSFETs are still operating in the kink region at liquid helium temperature and the open-loop gain of the opamp remains low. Finally, we want to point out the consistency of the high frequency open-loop gain beyond the rolloff point at all temperatures. This is evidence that the compensation capacitor, a metal-oxide/silicon type, is still functioning at low temperatures.

All operational amplifiers have a characteristic input offset voltage due to the mismatching of internal transistors and resistors. This voltage is largely random and varies between otherwise identical opamps.[19] The ICL7611-DMTV has a maximum offset voltage of 15 mV at room temperature and an overall maximum of 20 mV from 218 to 398 K.[16] As seen in Fig. 8 the input offset voltage remains within the general specification over our entire temperature range. In addition, the opamps internal offset nulling capability was always able to adjust this value to zero. In any case, the input offset voltage presents no hindrance to operation at any temperature.

This work will allow the use of cold electronics in a wide range of circuits which can be made more complex than previous simple MOSFET circuits. In addition, the opamp can be used at liquid helium temperature, not just down to 30 K (the lowest operating temperature to date).[11] The addition of an all MOSFET opamp to a low temperature measurement system can reduce capacitive coupling and pickup noise. As a result measurements will be faster and more accurate.

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