Evaluation of Voltage Reference Circuits and N-Channel Field Effect Transistors at Low Temperatures

Richard Patterson, NASA GRC, Richard.L.Patterson@grc.nasa.gov
Ahmad Hammoud, QSS Group, Inc./NASA GRC
Scott Gerber, ZIN Technologies, 300 Aerospace Parkway, Brook Park, Ohio 44142

Background

Many deep space and planetary exploration missions require power electronic components and systems that can operate reliably and efficiently in cryogenic temperature environments. Some of these missions include Mars Exploration Rovers (MER), Next Generation Space Telescope (NGST), Europa Orbiter, and Galaxy Explorer (GALEX), to name a few. Presently, spacecraft and probes operating in the cold environment of deep space carry on-board an accessory heating system in order to maintain an operating temperature for the electronics of approximately 20 °C. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space, but also reduce spacecraft size and weight by eliminating the heating units and associated structures, thereby reducing system development and launch costs, improving reliability, and increasing lifetime.

In a collaborative effort between NASA's Glenn Research Center (GRC), Goddard Space Flight Center (GSFC), and the Jet Propulsion Laboratory (JPL) under the NASA Electronic Parts and Packaging (NEPP) Program, the effects of extreme temperature and thermal cycling on various electronic devices and circuits are being investigated. This summary presents some of the results obtained on the evaluation of voltage reference and power switching devices under extreme temperature exposure.

Voltage Reference Circuits

Two circuit boards, populated with different voltage reference integrated circuit (IC) chips and a few passive components, were designed and built for evaluation in the temperature range of +25 °C to -180 °C. The circuits were characterized at test temperatures of 25, 0, -40, -80, -100, -120, -140, -160 and -180 °C in a liquid nitrogen cooled environmental chamber. Limited thermal cycle testing was also performed [1-2]. The plastic-packaged voltage reference IC chips were comprised of Linear Technology LT1461 and Analog Devices AD780BR. The LT1461 device is a low dropout micropower bandgap voltage reference with low drift and very high accuracy. The device draws very little current (35 µA) and is capable of providing an output drive current of 50 mA [3]. The low supply current makes it ideal for low power and portable applications, and its output current capability makes it suitable for high power requirements such as power supplies, analog-to-digital and digital-to-analog converters, and precision regulators. The device provides a steady output of 2.5 V from inputs up to 20 V, and it is specified for operation from -40 °C to +125 °C. The AD780BR counterpart is an ultrahigh precision bandgap voltage reference that can provide a pin-programmable output of 2.5 V or 3.0 V from inputs between 4.0 V and 36 V. It can be used to improve the performance of high-resolution analog-to-digital and digital-to-analog converters due to its capacitive-load driving capability. The device is specified for operation from -40 °C to +85 °C with low temperature drift and low output noise [4]. A temperature output pin provided on the AD780 allows the device to be configured as a temperature transducer while providing a stable output reference voltage. It is capable of sourcing or sinking up to 10 mA and can be used in series or shunt mode, thus allowing positive or negative output voltages without external components. The two devices were evaluated in terms of their 2.5 V output voltage regulation under a wide range of input voltage. These characteristics were obtained at various temperatures and at three different load levels.

Figure 1 shows the deviation in the output voltage of the LT1461 device with respect to its room temperature value. The data, which is shown as a function of temperature, is depicted for input voltages of 3, 12, and 20 volts at three different load levels. It can be seen that the reference output voltage generally remains within specifications (2.499 to 2.501 V) between temperatures of 25 °C to -40 °C. Below -40 °C, however, the output voltage begins to fluctuate as the temperature is decreased. While the output voltage undergoes a slight increase with decrease in temperature for the no-load condition, it exhibits a decrease when a load is applied. The intensity of this drop in the output voltage seems to depend on both the levels of the input voltage and the applied load. For example, the decrease is most dramatic at the highest load level with input voltages of 12 and 20 volts, as seen in Figure 1. In addition, the beginning of this trend occurs at temperatures as low as -80 °C, as compared to -120 °C for the case of other load/input voltage combinations. Furthermore, the device exhibits unstable operation at the two extreme low temperatures of -160 °C and -180 °C. Instability was also observed at temperature as low as -80 °C only when an input voltage of 3 V was applied under high load condition. It is important to note that at test temperature of -180 °C, the device completely loses its voltage regulation and it tends to behave almost like a unity-gain amplifier stage.

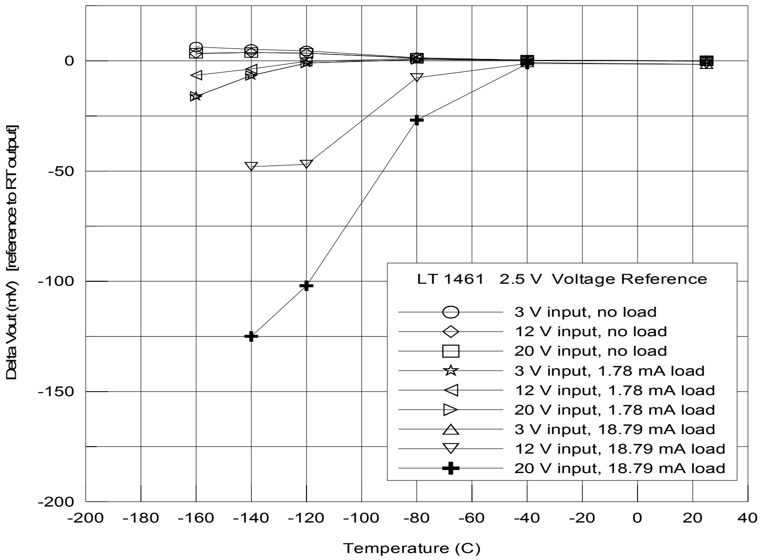

Figure 1. Deviation in output of LT1461 versus temperature at different test conditions.

The deviation in the output voltage of the AD780BR device with respect to its room temperature value is shown in Figure 2. The data, which is shown as a function of temperature, is depicted for all input voltage and load level combinations. It can be seen that the reference output voltage remains within specifications (2.499 to 2.501 V) between temperatures of 25 °C to -40 °C.

Between -40 °C and -120 °C, however, the output voltage begins to decrease very slowly as the temperature is decreased. In addition, the device exhibits unstable operation at the two extreme low temperatures of -160 °C and -180 °C. Instability was also observed at the test temperature of -140 °C only when an input voltage of 4 V was applied under no load condition. It is important to note that if the output specifications were broadened to cover a range of 2.495 V to 2.501 V, the device would be useful down to temperatures of -120 °C.

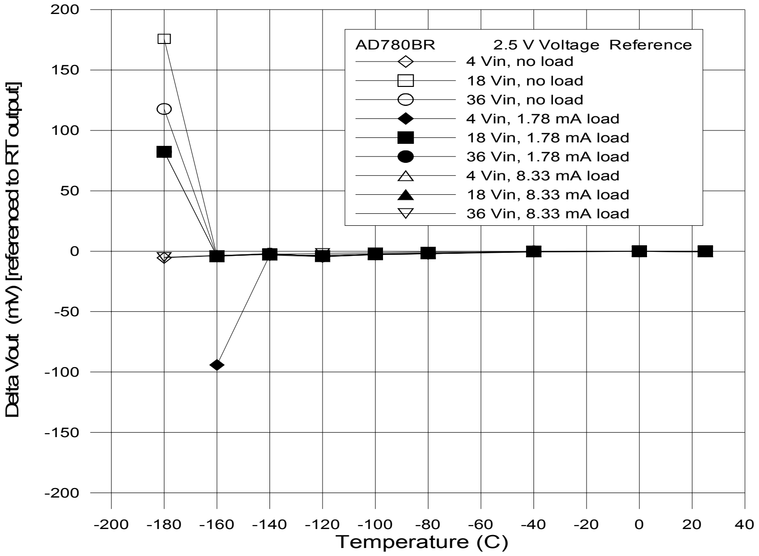

Figure 2. Deviation in output of AD780 versus temperature at different test conditions.

Power Switching Devices

An N-channel Silicon-On-Insulator (SOI) power field effect transistor (FET) device, Honeywell HTANFET, along with a control device (a standard "non-SOI" power FET), International Rectifier IRFD110 HEXFET Power MOSFET, were characterized in the temperature range of +20 °C to –190 °C. Performance characterization was obtained in terms of their gate threshold voltage (VGS[th]), drain-to-source on-state resistance (RDS[on]), and drain current (ID) versus drain-to-source voltage (VDS) family curves at various gate voltages (VGS). These properties were obtained using a digital curve tracer. The test temperatures at which these devices were investigated were: 20 °C, -50 °C, -75 °C, -100 °C, -125 °C, -150 °C, -175 °C, and -190 °C. Limited thermal cycling testing was also performed on the devices. These tests consisted of subjecting the devices to a total of five thermal cycles between +20 °C and -190 °C. Table I shows some of the operating specifications for the HTANFET and IRFD110 devices tested.

Figure 3 shows the output characteristics of the IRFD110 MOSFET at room temperature (20 °C). The output characteristics are defined as drain current (ID) versus drain-to-source voltage (VDS) family curves at various gate voltages (VGS). Gate voltages (VGS) utilized were 3.0V to 8.0V in steps of 0.5V. Note that no output was obtained with VGS equal to 3.0V, which is below the gate threshold voltage of 3.03 volts. Figure 4 shows the output characteristics of the same device at -190 °C. Two temperature-induced effects can be noted in the output characteristics of the device with change in the test temperature. The first is the downward shift of the VGS curves due to the increase in the gate threshold voltage with decreasing temperature. There is also a leftward shift of the VGS curves, especially at VGS ≥ 6.0V. This shift is primarily due to the decrease in on-state resistance with decreasing temperature.

Table I. Manufacturer's specifications of devices tested [5-6].

Device	Symbol	Parameter	Rating	Units
HTANFET	$T_{(oper)}$	Operating temperature	–55 to +225	°C
	I_D	Continuous drain current	* 1 max	A
	$V_{(BR)DSS}$	Drain-source breakdown voltage	* 90 min	V
	$R_{DS(on)}$	Drain-to-source on-state resistance, VGS=5V & ID=0.1A	* 0.4 typ	Ω
	$V_{GS\ (th)}$	Gate threshold voltage	* 1.6 typ * 2.4 max	V
	$V_{GS\ (max)}$	Maximum gate-to-source voltage	10	V
IRFD110	$T_{(oper)}$	Operating temperature	–55 to +175	°C
	I_D	Continuous drain current	* 1 max	A
	$V_{(BR)DSS}$	Drain-source breakdown voltage	* 100 min	V
	$R_{DS(on)}$	Drain-to-source on-state resistance, VGS=10V & ID=0.6A	* 0.54 max	Ω
	$V_{GS\ (th)}$	Gate threshold voltage	* 2.0 min * 4.0 max	V
	$V_{GS\ (max)}$	Maximum gate-to-source voltage	20	V

* Operating condition T = 25 °C.

The output characteristics of the HTANFET SOI MOSFET at room temperature are shown in Figure 5. Gate voltages (VGS) utilized in this test were between 1.5V to 6.0V. Once again, a VGS level exceeding the gate threshold voltage value must be applied for the device to produce any output. Figure 6 shows the output characteristics of the same device at -190 °C. Similar to its IRFD110 counterpart, the HTANFET device exhibited changes in its output characteristics with temperature. These changes, which are reflected by the shift and steepness of the family curves, are attributed to the increase in the gate threshold voltage and the decrease in the on-state resistance as temperature is decreased.

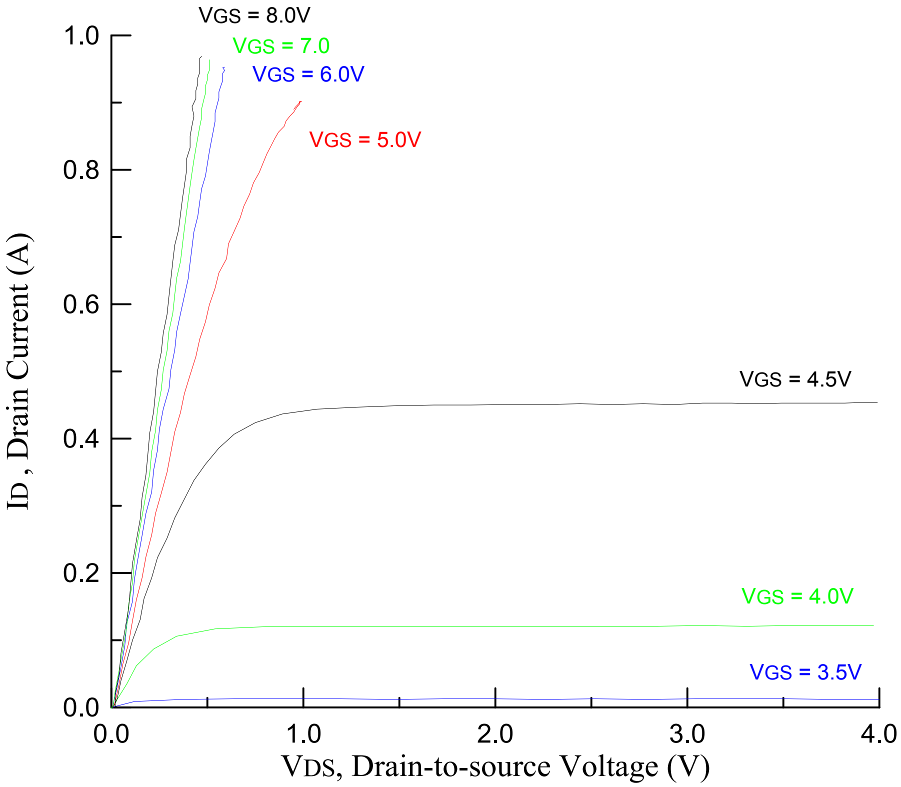

Figure 3. Output characteristics of the IRFD110 device at 20 °C.

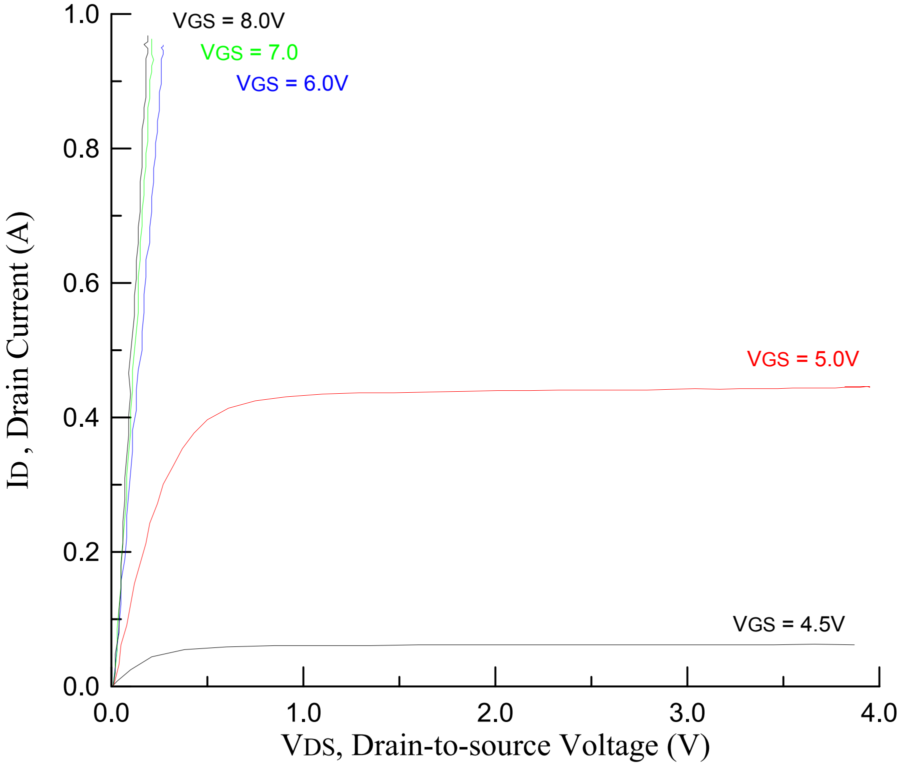

Figure 4. Output characteristics of the IRFD110 device at -190 °C.

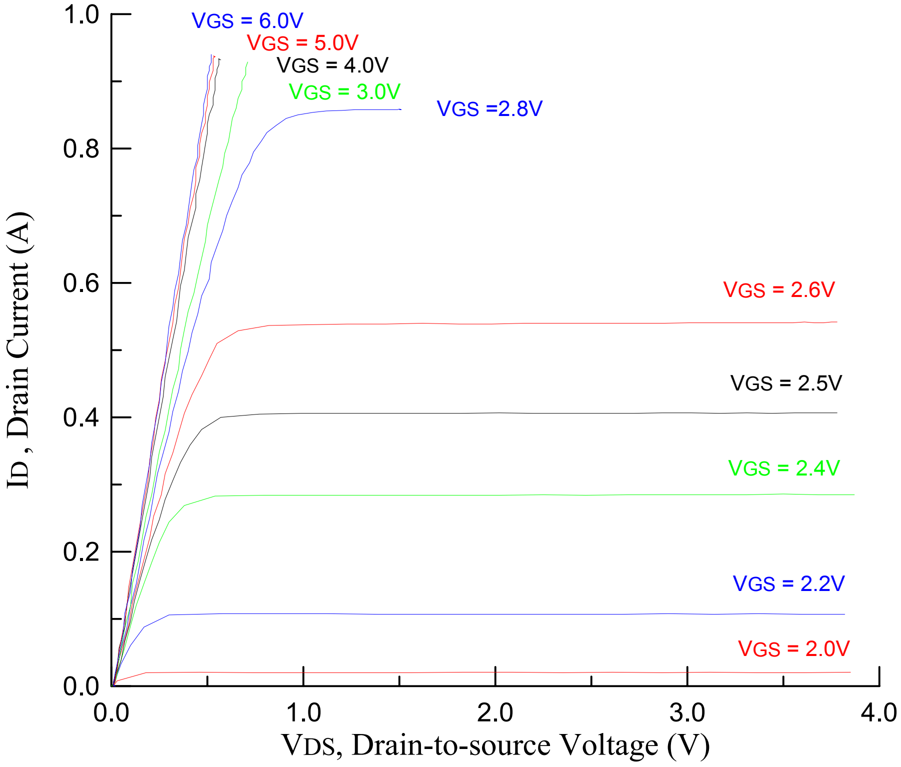

Figure 5. Output characteristics of the HTANFET device at 20 °C.

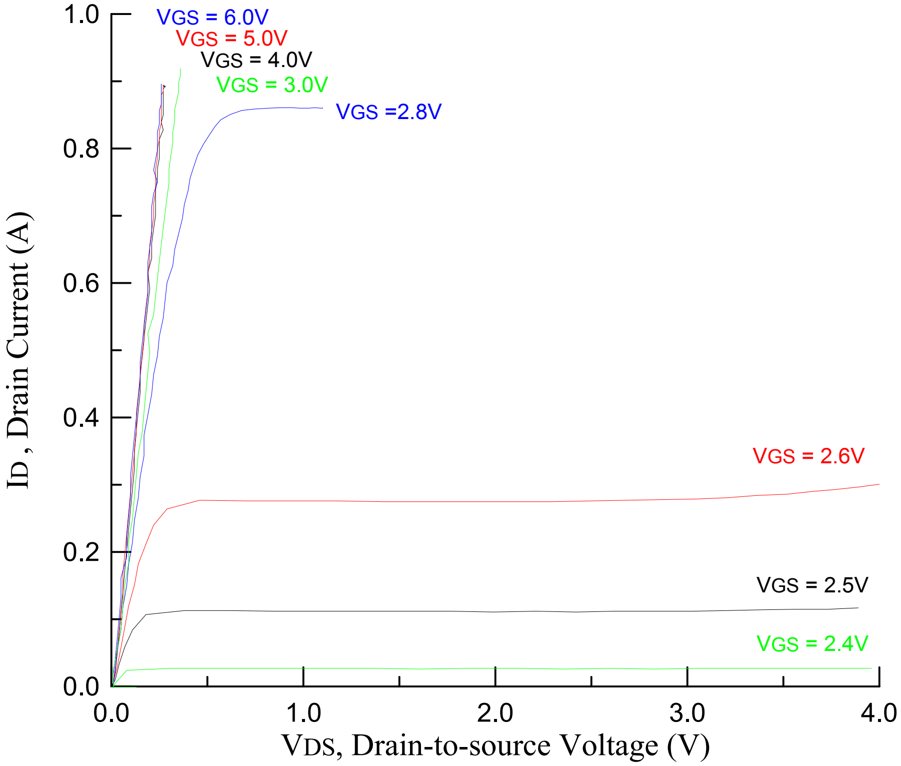

Figure 6. Output characteristics of the HTANFET device at -190 °C.

Limited thermal cycling (five cycles between +20 °C and -190 °C) of both devices appeared not to influence their characteristics as no changes occurred in the operational behavior of either device. For example, the pre- and post-cycling values of both the gate threshold voltage and the on-state resistance of the two devices remain almost the same as shown in Table II.

Table II. Effects of thermal cycling on gate threshold voltage (VGS[th]) and on-state resistance (RDS[on]).

	$V_{GS(th)}$ (V)		$R_{DS(on)}$ (Ω)	
Device	Before (20 °C)	After 5 cycles (20 °C)	Before (20 °C)	After 5 cycles (20 °C)
IRFD110	3.03	3.04	0.49	0.48
HTANFET	1.64	1.65	0.58	0.59

Remarks

An ongoing Low Temperature Electronics Program at the NASA Glenn Research Center focuses on the development of electronic devices and systems geared for operation under extreme temperatures in deep space applications. Major activities in this program include characterization and reliability assessment of advanced and commercial-off-the-shelf (COTS) components and circuits for use in low temperature environments. Extensive collaboration and coordination exist with the NASA Electronic Parts and Packaging (NEPP) and the NASA Electronic Parts Assurance Group (NEPAG) Programs in pursuing these efforts.

References

1. “Evaluation of Linear Technology LT1461 Voltage Reference at Low Temperature,” NASA GRC white paper.
2. “Performance of Analog Devices AD780BR Voltage Reference at Cryogenic Temperatures,” NASA GRC white paper.
3. Linear Technology LT1461-2.5 Micropower Precision Low Dropout Series Voltage Reference Data Sheet.
4. Analog Devices AD780 High Precision Reference Data Sheet, Rev. B.
5. HTANFET High Temperature N-Channel Power FET Data Sheet, Honeywell.
6. IRFD110 HEXFET Power MOSFET Data Sheet, International Rectifier.

Acknowledgments

This work was performed under the NASA Glenn Research Center GESS Contract # NAS3-00145. Support was provided from the NASA Electronic Parts and Packaging (NEPP) Program, EPAC Task “Effects of Wide Temperature Exposure on Characteristics of Plastic Encapsulated COTS Components for Space Applications” and EPAC Task “Reliability of Cold Interconnects.” The authors acknowledge the support of Dr. Reza Ghaffarian and Dr. Rajeshuni Ramesham of NASA JPL, and Dr. Ashok Sharma of NASA GSFC.

Note: This document summarizes the following three full-length test reports, which are posted on the NEPP Web site: Low Temperature Evaluation of the HTANFET Silicon-on-Insulator (SOI) N-Channel Field Effect Transistor, Performance of the Analog Devices AD780BR Voltage Reference at Cryogenic Temperatures, and Evaluation of the Linear Technology LT1461 Voltage Reference at Low Temperatures. Respectively, they can be accessed at http://nepp.nasa.gov/index_nasa.cfm/619/3B717CDF-DFF7-473D-850D1467C0C91C21/, http://nepp.nasa.gov/index_nasa.cfm/619/36AA56DF-052E-496B-AD0FB4E51537354E/, http://nepp.nasa.gov/index_nasa.cfm/619/32152DC5-86BC-4222-84E6BA27FD442279/.