NASA/TM—2001-210235

Development of Electronics for Low-Temperature Space Missions

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January 2001

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Prepared for the
Fourth European Workshop on Low Temperature Electronics
sponsored by the European Space Agency
Noordwijk, The Netherlands, June 21–23, 2000

National Aeronautics and
Space Administration

Glenn Research Center

January 2001

Available from

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DEVELOPMENT OF ELECTRONICS FOR LOW-TEMPERATURE SPACE MISSIONS

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SUMMARY

Electronic systems that are capable of operating at cryogenic temperatures will be needed for many future NASA space missions, including deep space probes and spacecraft for planetary surface exploration. In addition to being able to survive the harsh deep space environment, low-temperature electronics would help improve circuit performance, increase system efficiency, and reduce payload development and launch costs. Terrestrial applications where components and systems must operate in low-temperature environments include cryogenic instrumentation, superconducting magnetic energy storage, magnetic levitation transportation systems, and arctic exploration.

An ongoing research and development project for the design, fabrication, and characterization of low-temperature electronics and supporting technologies at NASA Glenn Research Center focuses on efficient power systems capable of surviving in and exploiting the advantages of low-temperature environments. Supporting technologies include dielectric and insulating materials, semiconductor devices, passive power components, optoelectronic devices, and packaging and integration of the developed components into prototype flight hardware.

An overview of the project is presented, including a description of the test facilities, a discussion of selected data from component testing, and a presentation of ongoing research activities being performed in collaboration with various organizations.

INTRODUCTION

Electronic components and systems capable of low-temperature operation will be required for many future NASA space missions when smaller, lighter, and cheaper unheated spacecraft are desirable. These spacecraft include Mars orbiters, landers, and rovers; Europa oceanic exploratory probes; and spacecraft for outer planetary exploration and deep space probes. The table below shows typical operational temperatures for unheated spacecraft in the environments of the outer planets. For example, an interplanetary probe launched to explore the rings of Saturn would experience a temperature near the planet of about −183 °C. Low-temperature electronics would not only be able to survive hostile space environments but would also help to improve circuit performance, increase system efficiency, and reduce development and launch costs.

Mission	Temperature, °C
Mars	−20 to −120
Jupiter	−151
Saturn	−183
Uranus	−209
Neptune	−222
Pluto	−229

Presently, spacecraft operating in the cold environment of deep space carry a large number of radioisotope heating units (RHU's) to maintain an operating temperature of approximately 20 °C for the electronics (ref. 1). However, since the RHU's are always producing heat, even when the spacecraft may already be too hot, an active thermal control system is also required. In addition, RHU's are very expensive and require elaborate containment structures. Electronics capable of operation at cryogenic temperatures will not only tolerate the deep space environment but will also reduce system size and weight by eliminating RHU's and associated structures, thereby reducing system development and launch costs, improving reliability and lifetime, and increasing energy densities.

Besides deep space applications, low-temperature electronics have potential terrestrial applications in magnetic levitation transportation systems, medical diagnostics, cryogenic instrumentation, and superconducting magnetic energy storage systems. Systems incorporating power electronics designed for and operated at low temperatures are expected to be more efficient than systems using electronics designed for room-temperature operation. This improvement results from the better electronic, electrical, and thermal properties of the materials at low temperatures (refs. 2 and 3). In particular, the performance of certain semiconductor devices improves with decreasing temperature down to the temperature of liquid nitrogen (−196 °C) (refs. 3 and 4). At low temperatures, the majority of carrier devices demonstrate reduced leakage current and reduced latchup susceptibility. These devices also show higher speed resulting from increased carrier mobility and saturation velocity (refs. 3 to 5). For example, the power metal-oxide-semiconductor field-effect transistor (MOSFET) has lower conduction losses at low temperatures because of the reduction in the drain-to-source resistance $R_{DS(on)}$ resulting from increased carrier mobility (refs. 4, 6, and 7).

GLENN LOW-TEMPERATURE ELECTRONICS PROJECT

The goal of the Low-Temperature Electronics Project at NASA Glenn Research Center is to develop and demonstrate for deep space missions reliable, efficient power systems that are capable of surviving in and exploiting the advantages of low-temperature environments. Research is being conducted on devices and systems for use down to cryogenic temperatures (−196 °C). The targeted systems are mission driven and include converters, inverters, controls, digital circuits, and special-purpose circuits. Various design topologies were used in the initial research to produce the successful low-temperature operation and cold restart of several dc-dc converters (with outputs from 5 to 1000 W) (refs. 1, 4, and 7). Some of these circuits employed superconducting inductors.

In support of system development, device and component research is underway in critical areas of passive and active components, optoelectronic devices, and energy generation and storage. Initially, commercial-off-the-shelf (COTS) devices and components are characterized in terms of their performance at low temperatures. When viable commercial devices fail to meet mission requirements, development of new advanced components is undertaken.

In addition to research and development to fill the technology gaps in low-temperature power electronics, research is also being conducted on the thermal aspects of packaging, integration, and cycling.

Glenn Low-Temperature Facilities

At Glenn Research Center, test facilities exist for the development and analysis of power and control circuits that can operate at power levels from direct current to several megahertz over a wide temperature range. These facilities consist of several liquid-nitrogen-cooled environmental chambers in which a circuit can be operated with controlled temperatures from −196 to 300 °C. The chambers have built-in controllers that allow selecting the desired temperature rate of change and soak times. Computer-controlled instrumentation is interfaced with the environmental chambers using the Institute of Electrical and Electronics Engineers (IEEE) GPIB–488 standard for data acquisition. The measurement equipment includes a digital signal analyzer, pattern generators, precision digital impedance meters, high-speed-storage oscilloscopes, and a precision temperature controller and recorder. Finally, various electronic and resistive loads ranging from milliwatts to kilowatts are available.

A unique computerized control system is used with a cryopumped vacuum chamber containing a cryocooled sample holder for the characterization of commercial and developmental semiconductor devices and components. This facility is capable of in situ current-voltage (I-V) and capacitance-voltage (C-V) characterization of semiconductor devices from −248 to 23 °C.

Glenn has designed computer-controlled facilities for long-term, low-temperature thermal cycling and characterization of electrical and physical properties of dielectrics and capacitors. Facilities have also been built for reliability studies and life testing of passive and active devices in spacelike environments under multistress conditions. Typical research that can be conducted using these unique facilities includes dielectric material characterization, investigation of dc and ac breakdown voltages, resistivity measurements, and studies of switching characteristics and of the overall performance of an electronic system (e.g., its regulation and efficiency).

In optoelectronics, Glenn has facilities to characterize and test fiber-optic sources, receivers, cables, connectors, and other components and assemblies at temperatures from −196 to 300 °C. Although most low-temperature testing on fiber-optic components has concentrated on 1300 nm, tests can be conducted at other wavelengths.

Other onsite supporting research facilities include physical, chemical, and mechanical test chambers and diagnostic stations. The characterization of materials and evaluation of systems and components in a spacelike environment (comprising the qualities of vacuum, plasma, ultraviolet radiation, and atomic oxygen found in space) can be achieved in multistress aging test rigs and facilities.

Low-Temperature Research and Development Activities

Components that are being characterized include semiconductor switching devices, capacitors, batteries, temperature transducers, and analog-to-digital ac converters.

Figure 1 shows the drain characteristics in I-V curves for an IRF541 n-channel HEXFET (trademark for International Rectifier Power MOSFET's) MOSFET at 20 °C (labeled 1, 2, and 3 for three different gate voltages). This device is used as a power switch in low-power dc-dc converters. Figure 2 shows the drain characteristics in I-V curves for the same device at −196 °C (with markings for the same gate voltages). Note that the drain current has dropped by 3 orders of magnitude at the lower temperature.

Metal-Semiconductor Field-Effect Transistor (MESFET)

The drain characteristics in I-V curves for an NE76118 GaAs (gallium arsenide) n-channel metal-semiconductor field-effect transistor (MESFET) at 20 °C are shown in figure 3. Figure 4 shows the drain characteristics in I-V curves for the same device at −196 °C. For the gate voltage labeled 4, drain current drops by about 10 percent at −196 °C. At the gate voltage labeled 7, the drop in the drain current is more severe at the lower temperature. Note that the drain current shows a milder drop at the lower temperature for the GaAs device than for the silicon FET device.

The change in capacitance for three types of capacitors at temperatures ranging from 25 to −190 °C at a frequency of 20 kHz is shown in figure 5. The mica capacitor exhibits excellent stability with temperature change, whereas the electrolytic tantalum capacitor decreases significantly in capacitance when the test temperature goes below −25 °C. In fact, below −80 °C, the capacitance drops to zero. Unlike its electrolytic counterpart, the solid tantalum capacitor exhibits only a slight decrease in capacitance as the temperature is decreased. This reduction in capacitance amounts to only about 10 percent, even at temperatures as low as −190 °C.

The effect of temperature at various loads on the current-voltage characteristics of a lithium primary battery is depicted in figure 6. The current-voltage performance of the battery decreases with decreasing temperature. Reduced battery capacity with decreasing temperature is more noticeable at higher loads. Note that the effect of low-temperature exposure on the performance of a particular device ranges from minimal to detrimental depending on several parameters, such as the device internal structure, material constituents and compatibility under extreme temperatures, and packaging topologies.

Several dc-dc converters were also built and characterized at low temperatures in-house. The converters were designed or modified to operate in the range from room temperature to −196 °C using commercially available components such as complementary metal-oxide-silicon (CMOS)-like devices and MOSFET switches. These systems had output power ranging from 5 W to 1 kW with switching frequencies from 50 to 200 kHz. The pulse-width modulation technique was implemented in most of these systems with both open- and closed-loop control. The topologies included buck, boost, multiresonant, push-pull, and full-bridge configurations (refs. 8 to 11).

Figure 7 shows the efficiency of a commercial dc-dc converter as a function of temperature for various input voltages and output currents. In general, efficiency decreases as the temperature drops, and heavy loads are more efficient than light loads. The output voltage of the same converter module under the same test conditions is depicted in figure 8. At low loads, the converter exhibits excellent voltage regulation stability from 20 to −120 °C. At heavy loads, however, the converter output voltage tends to decrease with decreasing temperature. This decrease becomes more evident at temperatures lower than −40 °C.

CONCLUDING REMARKS

An overview of the Low-Temperature Electronics Project at NASA Glenn Research Center was given. The project is focused on developing selected mission-driven power systems and supporting technologies for low-temperature operation. Ongoing activities include research and evaluation of dielectric and insulating material, development and testing of low-temperature power components, and integration and demonstration of electronic systems. Other supporting research includes long-term reliability assessment of power devices and integrated circuits, and observation of the effects of low-temperature exposure on device interconnection and packaging.

The Glenn in-house low-temperature test facilities for material testing and characterization were described, and evaluations of components and systems were presented with some preliminary experimental data. Use of test facilities with the proper diagnostic and analytical tools and coordination of research and development with other agencies, academia, and the aerospace industry will certainly contribute to meeting the needs of future space power and new electrical systems in general.

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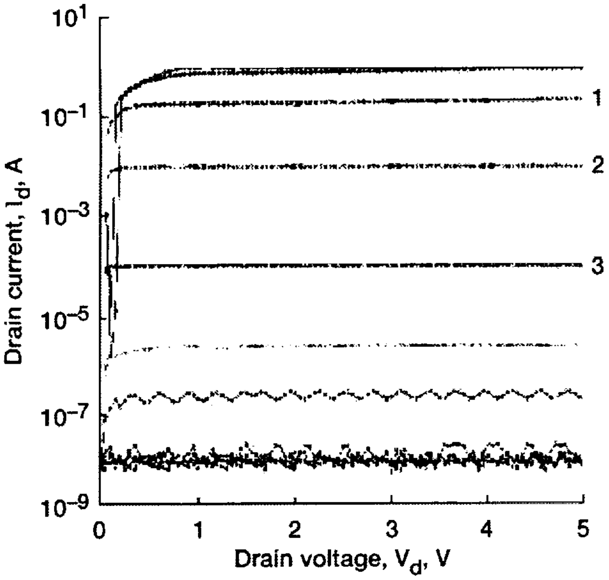

Figure 1.—Drain characteristics in in situ current-voltage (I-V) curves of IRF541 n-channel HEXFET™ power metal-oxide-semiconductor field-effect transistor (MOSFET) at 20 °C. Lines labeled 1, 2, and 3 correspond to the same lines in figure 2.

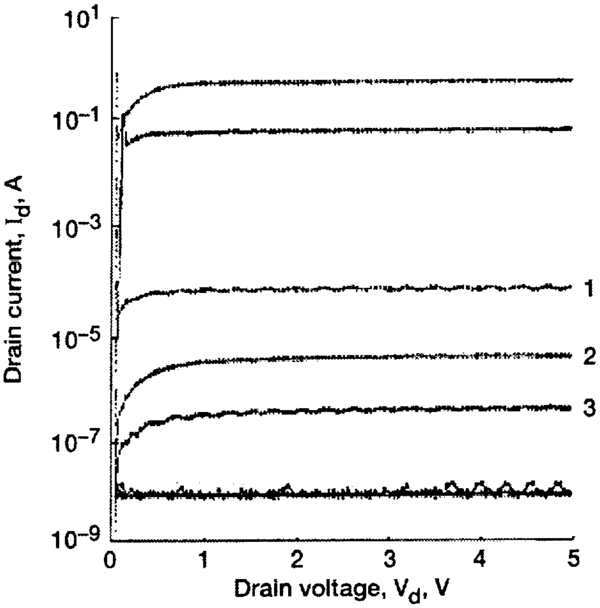

Figure 2.—Drain characteristics in in situ current-voltage (I-V) curves of IRF541 n-channel HEXFET™ MOSFET at −196 °C. Lines labeled 1, 2, and 3 correspond to the same lines in figure 1.

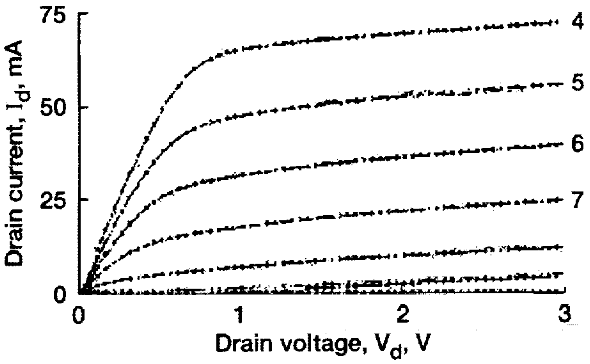

Figure 3.—Drain characteristics in in situ current-voltage (I-V) curves of NE76118 GaAs n-channel metal-semiconductor field-effect transistor (MESFET) at 20 °C. Lines labeled 4, 5, 6, and 7 correspond to the same lines in figure 4.

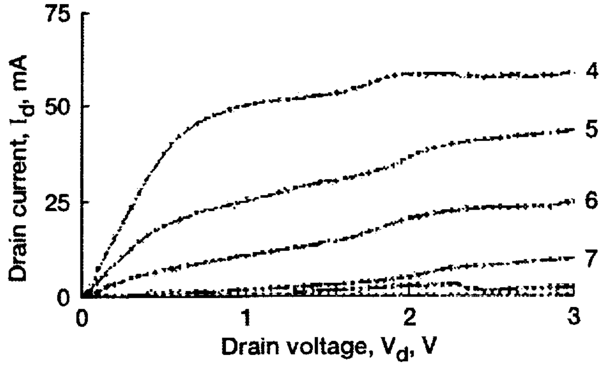

Figure 4.—Drain characteristics in in situ current-voltage (I-V) curves of NE76118 GaAs n-channel MESFET at −196 °C. Lines labeled 4, 5, 6, and 7 correspond to the same lines in figure 3.

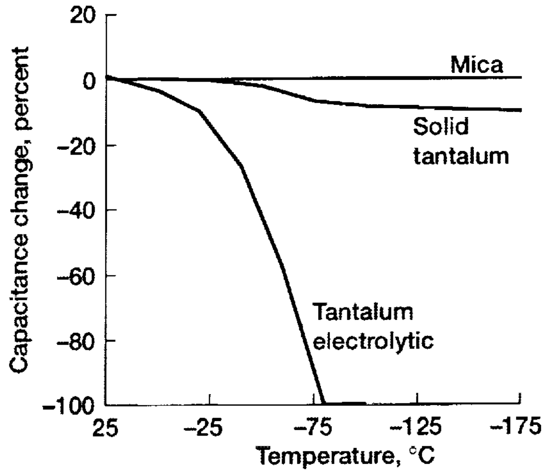

Figure 5.—Capacitance change with temperature for three types of capacitors at frequency of 20 kHz.

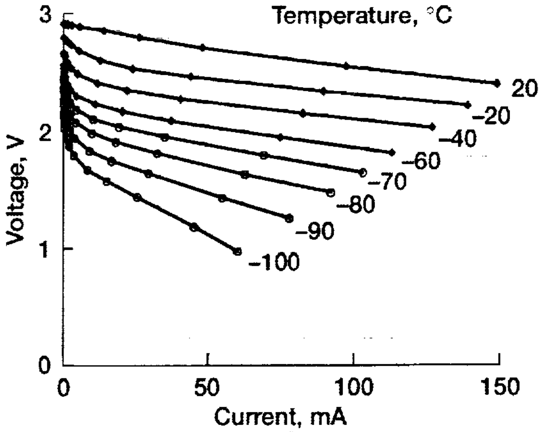

Figure 6.—Effect of temperature at various loads on current-voltage characteristics of lithium primary battery.

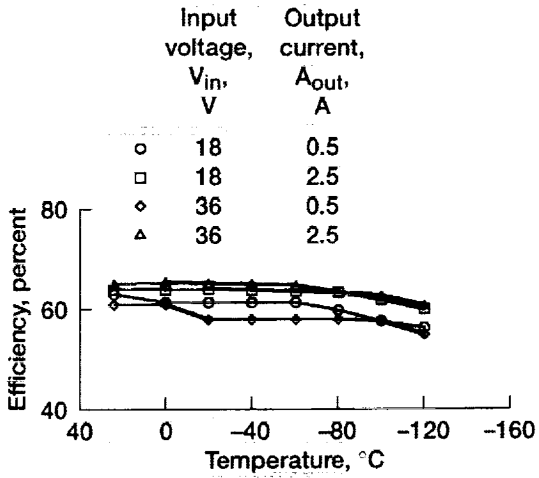

Figure 7.—Efficiency of commercial dc-dc converter as function of temperature for various input voltages and output currents.

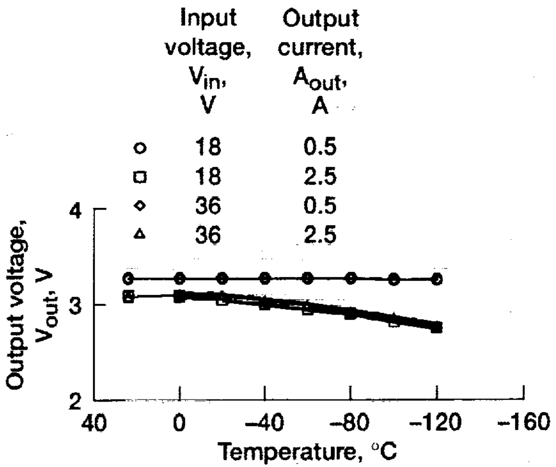

Figure 8.—Output voltage of same commercial dc-dc converter (from figure 7) as function of temperature for various input voltages and output currents.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** January 2001	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Development of Electronics for Low-Temperature Space Missions

5. FUNDING NUMBERS

WU–755–A4–12–00

6. AUTHOR(S)

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Scott S. Gerber, and Eric Overton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–12354

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2001-210235

11. SUPPLEMENTARY NOTES

Prepared for the 4th European Workshop on Low Temperature Electronics sponsored by the European Space Agency, Noordwijk, The Netherlands, June 21–23, 2000. Richard L. Patterson, John E. Dickman, and Eric Overton, NASA Glenn Research Center; Ahmad Hammoud and Scott S. Gerber, Dynacs Engineering Company, Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142. Responsible person, Richard L. Patterson, organization code 5480, 216–433–8166.

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14. SUBJECT TERMS

Electronic equipment; Spacecraft; Cryogenic temperature

15. NUMBER OF PAGES

12

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102