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Commercial Electronic Components and Silicon-on-Sapphire ICs at Extreme Cryogenic Temperatures

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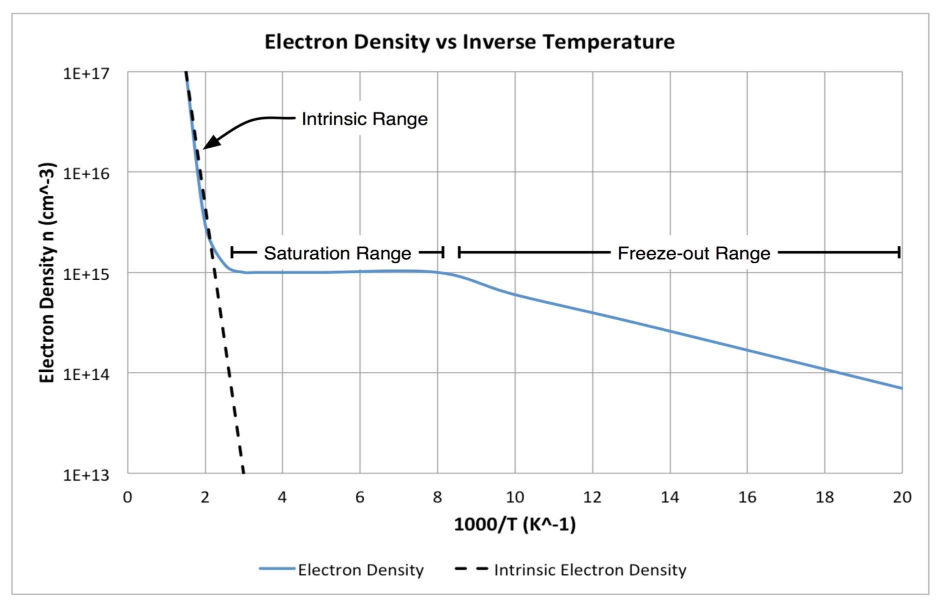
Abstract

Electronic circuits generally perform well at moderately cold temperatures, but can show interesting and negative behaviors as extreme cryogenic regimes are reached. This paper looks at the performance of Silicon-on-Sapphire (SOS) and selected commercial silicon devices operating to temperatures of 77 Kelvin and below. While expected freeze-out behavior is observed clearly in a commercial silicon device (1N4001 rectifier), SOS resistors and transistors tested using the same setup did not experience this effect, and in some cases stayed reasonably well-behaved to 5 Kelvin. However, unlike other reported investigations of SOS devices operating at extreme cryogenic temperatures, strong kink-effects were observed, especially for devices operating at low Vgs overdrives (weak inversion). These results point out both problems and promises of developing electronics in an RF and mixed-signal IC process suitable for use in exploring the surface of outer-planets and their moons.

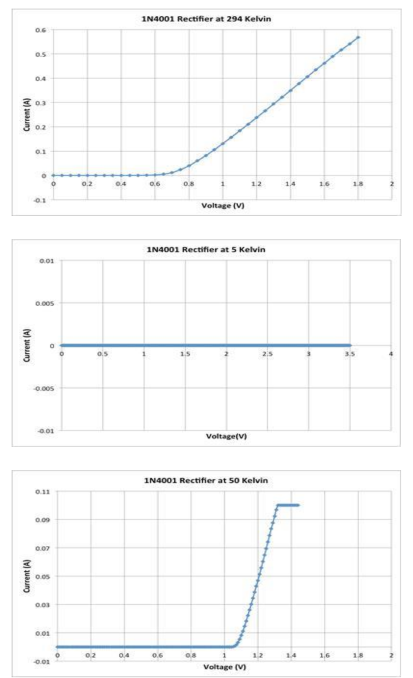
Carrier Freeze-out

Carrier freeze-out is a condition that occurs at cryogenic temperatures, where electrons do not have sufficient energy to enter the conduction band. In the case of an n-type material, electrons are bound to the donors. Semiconductor devices that have entered a freeze-out condition may fail to operate correctly because all the electrons are bound to the donors.

The 1N4001 bulk process rectifier experienced total carrier freeze-out when tested at 5 Kelvin, proving the Janis system could induce the phenomenon. The device was not able to flow current even with 3.5 volts applied. Current began to flow again when the rectifier was operated at 50 Kelvin, verifying the device was still functional.

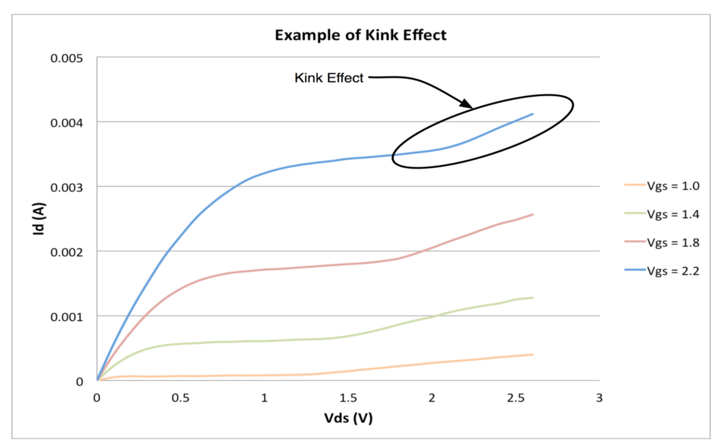


Electron Density vs 1/T (J. Singh, Semiconductor Devices, Wiley, 2001)



Kink Effect

The kink effect is observed in transistors where the output resistance decreases while the device is operated in the saturation region. Figure 2 shows an example of the kink effect in an NFET.
The kink effect in NFETs is caused by holes moving from the drain to source under the channel and effectively lowering the threshold voltage, which causes an increase in drain current, Id. The phenomenon is typically seen in devices with a floating body contact or in cryogenic environments [Kato, Wada, Taniguchi, IEEE].



NFET Example of the Kink Effect

Experimental Setup

Two cryogenic cooling systems were used to obtain measurements. The first system used was a Janis ST-100, which uses liquid helium to achieve a temperature of 5 Kelvin. The second system consisted of a Helix CTI-Cryogenics Model-22 Refrigerator and Model SC Compressor.

The Janis ST-100 system requires a continuous flow of liquid helium to achieve temperatures down to 5 K. The data collection was automated with a previously designed LabVIEW based FET curve tracer program controlling two Agilent E3641A power supplies and an Agilent 34401A DMM.

The CTI-Cryogenics Model-22 system is a closed cycle helium refrigeration system. Pure helium is compressed and allowed to expand which extracts heat from the cold head inside the system where the DUT is located. The data collection is automated by a new LabVIEW program, which controls two Agilent E3641A power supplies and an Agilent 34401A DMM.

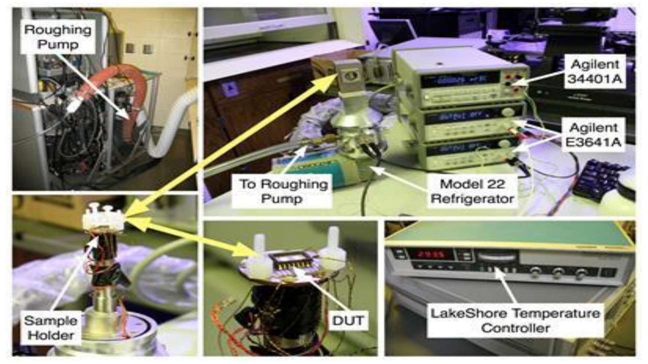


Photo of the CTI-Cryogenics System Setup

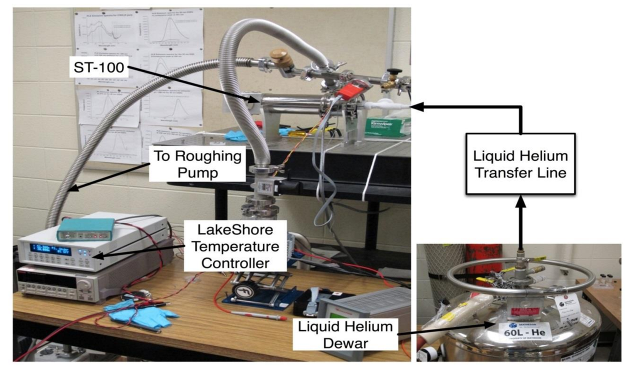
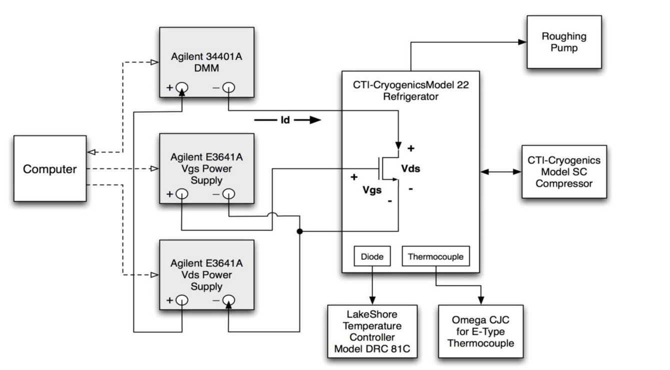
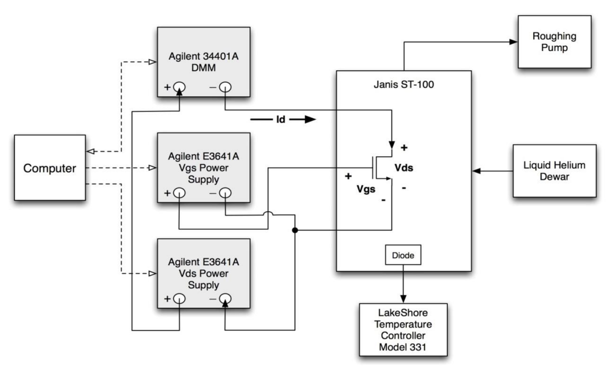


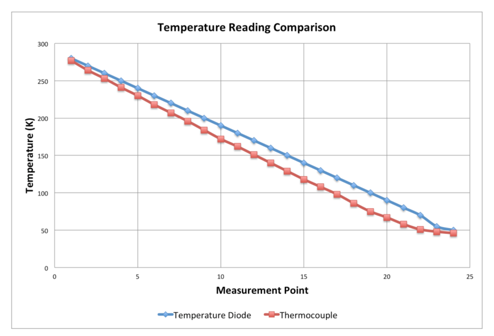
Photo of the Janis ST-100 Cryogenic Setup

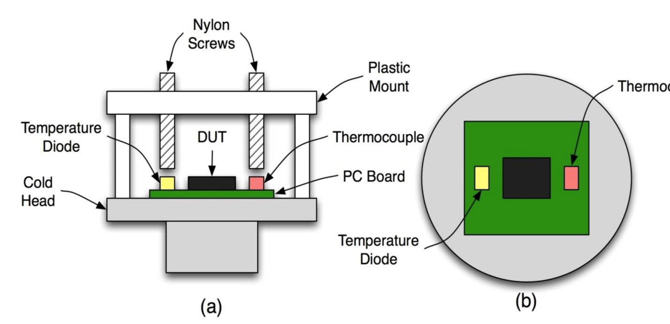

CTI-Cryogenics System Experimental Setup Diagram


Janis ST-100 Experimental Setup Diagram

Temperature Validation

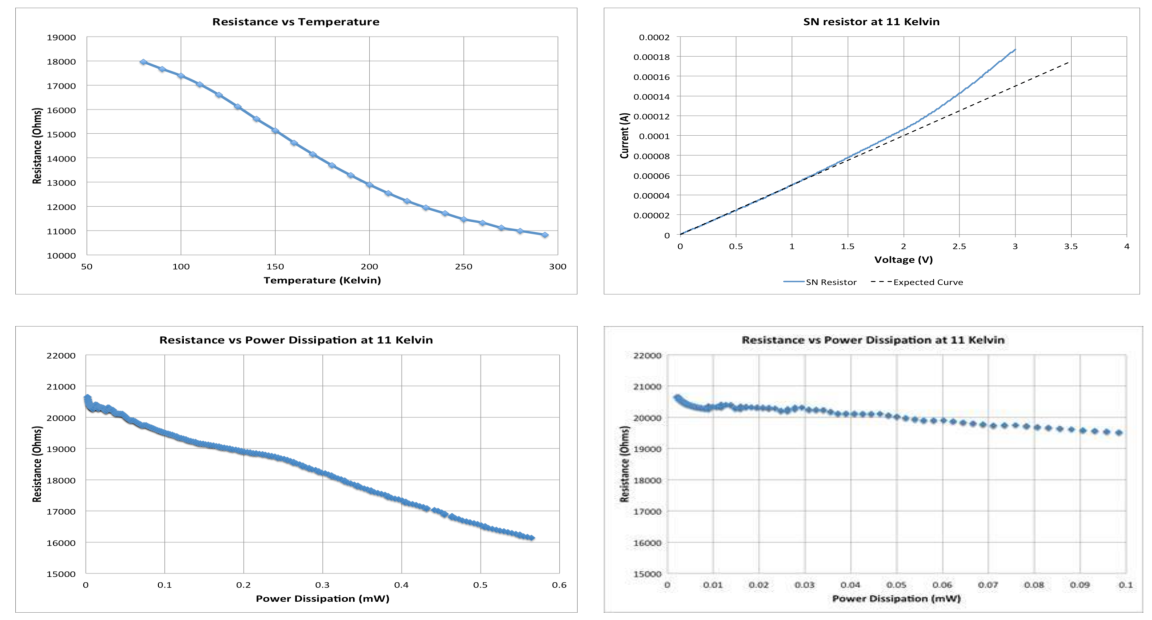
The CTI-Cryogenics systems had a temperature diode sensor and an E-type thermocouple. Taking a measurement at room temperature and while submerged in liquid nitrogen validated the temperature sensors' accuracies. The sensors were about 4 Kelvin off at room temperature but read the same temperature at 77 K. Figure 3.5 shows how the sensors tracked each other while taking the CTI-Cryogenics system down to 50 Kelvin.





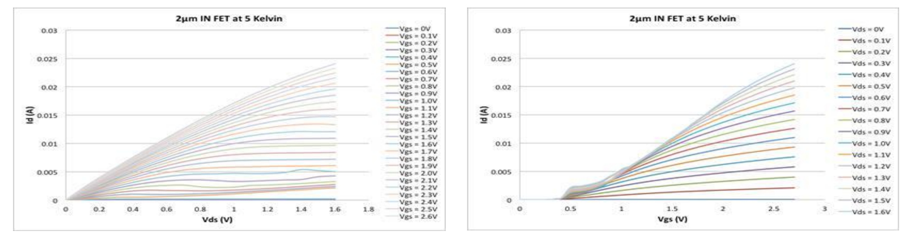
SOS Silicide Blocked (SN) Resistor

The SOS SN resistor never experienced carrier freeze-out but as the temperature decreased the resistance increased from 11kΩ at room temperature to 20.5kΩ at 11 Kelvin. The increase in the effective resistance is caused by a decrease of carriers in the conduction band while operating in the freeze-out region. Localized heating in the SN resistor caused a shift in the local operating temperature, skewing the results. Designers should keep localized heating in mind when driving semiconductor devices at high power dissipations because the local temperature could be significantly warmer than the ambient environment.



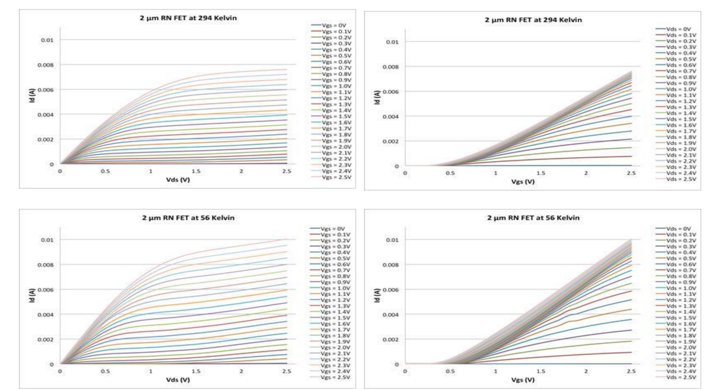
SOS 2µm Intrinsic (IN) FET

The lightly doped 2µm SOS IN FET never experienced carrier freeze-out even down to 5 Kelvin. The IN FET was thought to be more susceptible to carrier freeze-out but its resistance to the phenomenon suggests most SOS devices will operate down to 5 Kelvin.



SOS 2µm Medium Threshold (RN) FET

A 2µm SOS RN FET was tested at 294 and 56 Kelvin. The RN FET did not display kink effect characteristics at 294 Kelvin but when operated at 56 Kelvin the phenomenon became evident. The threshold voltage and current levels also increased at 56 Kelvin. The RN FET followed the same patterns seen in the previously tested devices.

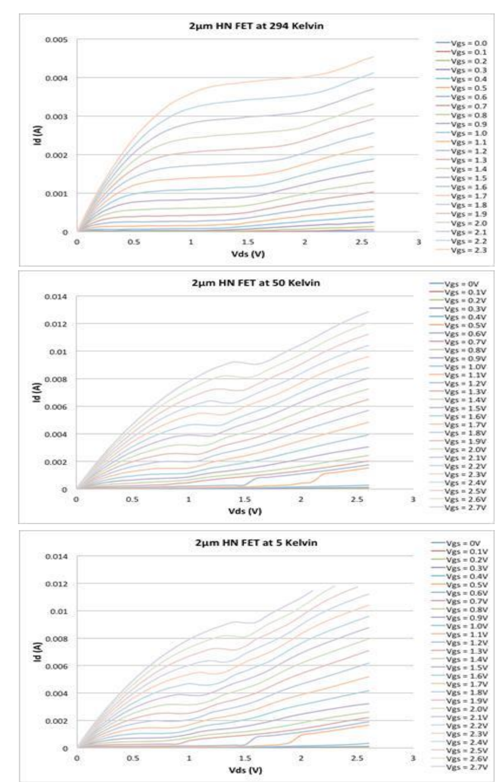


SOS 2µm High Threshold (HN) FET

The main observations with the HN FET measurements are:

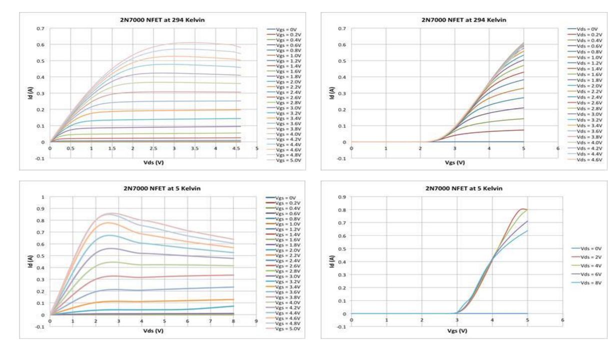
1. The kink effect becomes significant at cryogenic temperatures creating strong non-idealities in the Id curves.
2. Current levels and threshold voltages increase.
3. The threshold voltage appears to stop shifting once the temperature reached 50 Kelvin
4. The kink effect did not change much between 50 Kelvin and 30 Kelvin but did manifest a little earlier at 5 Kelvin.

Carrier freeze-out was never reached but the devices were clearly operating in the freeze-out region.



2N7000 Results

The 2N7000 bulk process NFET never experienced carrier freeze-out even down to 5 Kelvin.



Conclusions

When developing devices to operate in the cryogenic environments of the outer planets and their moons, there are a few characteristic changes designers need to consider. SN resistor values will steadily increase down to 5 Kelvin. Threshold voltages and current levels of transistors increase down to 50 Kelvin and then remain somewhat consistent to 5 Kelvin. The kink effect appears to occur at lower voltage levels as the temperatures decrease. HN FETs are not recommended for circuits designed for cryogenic temperatures because they appear to be unstable. Instead, RN or IN FETs should be used for their more predictable characteristics while in saturation at cryogenic temperatures.

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Any opinions, findings, and conclusions or recommendations in this material are those of the author(s) and do not necessarily reflect the views of the sponsor.