Cold-Capable, Radiation-Hardened SiGe BiCMOS Wireline Transceivers

Troy England, Chandim Chatterjee, Nelson Lourenco, Steven Finn, Laleh Najafizadeh, Stanley Phillips, Eleazar Kenyon, Ryan Diestelhorst, John Cressler
Georgia Institute of Technology

INTRODUCTION

Space-based electronic systems are required to be some of the most robust of any in the electronics industry, facing extremely wide temperature ranges and hazardous radiation that can cause unpredictable behavior. The most common mitigation procedure involves extensive shielding and temperature control in warm boxes or electronics vaults. Unfortunately, this practice increases size, weight, and power (SWaP) requirements.

Recently, there has been a paradigm shift that advocates moving away from these centralized solutions and towards distributed electronic systems. Distributed electronics have major benefits in remote sensing where the critical signal processing can be adjacent to sensors rather than in a centralized area in the vehicle. Distributed electronics also allow for point-of-load control, enabling better operation where previously long wires could induce parasitics that limit the performance of feedback networks.

For distributed electronics to be a viable alternative to their centralized counterparts, the heavy radiation shielding and temperature control must be lessened or eliminated. For this reason, silicon-germanium (SiGe) BiCMOS (SiGe heterjunction bipolar transistor (HBT) and Si CMOS) technology is becoming a popular choice for spaced-based electronics. SiGe BiCMOS provides excellent overtemperature and radiation performance while maintaining compatibility with conventional, high-volume, inexpensive Si manufacturing techniques.

The distributed approach also requires that the central processing unit communicate with multiple nodes throughout the vehicle. Often this leads to a vehicle-wide bus with multiple transmitters and receivers where both preprocessed data from sensors and commands from a system controller can easily travel. Two common standards for this type of communication are RS-485 and ISO 11898 because of their ease of use and existing hardware. Still, wide-temperature, radiation-hardened versions are needed.

This article presents SiGe BiCMOS transceivers designed for basic compatibility with the RS-485 and ISO 11898 standards, while operating over a 300 K temperature range, from 90 K to 390 K. The transceiver designs are based on similar architectures with customization for each standard. This work continues from previous research presented in [1], and an earlier version of the RS-485 transceiver, which was presented in [2]. Compared to the original, this new work expands the working temperature range, increases the transmitter output voltage swing, and widens the receiver input hysteresis range. Furthermore, the newly introduced ISO 11898 transceiver is shown to be tolerant to 2 Mrad of total ionizing dose (TID), and the transmitter is shown to be single-event hardened in a broad-beam heavy-ion environment.

The rest of this article will first cover the SiGe BiCMOS technology used in the designs. Second, it will review the specific application the transceivers were designed for. Next, the design and measurement of the RS-485 transceiver will be described. Then, the design, overtemperature measurement, total ionizing dose (TID) experiment, and broad-beam testing of the ISO 11898 transceiver will be presented. Finally, a summary of the results with opportunities for future expansion will be discussed.

SIGE TECHNOLOGY

One of the enabling forces behind the shift to localized, minimally shielded electronics in space-based systems is the flexibility of SiGe BiCMOS technology, specifically the SiGe HBT, to tolerate the extreme conditions presented by extraterrestrial environments. In the simplest view, SiGe HBTs are Si bipolar junction transistors (BJTs) with the addition of germanium in the base. The band gap is lowered proportionally to the germanium percent content. Using a combination of uniform and graded content along the current path creates dramatic improvements of device parameters like current gain, output conductance, broadband noise, maximum cutoff frequency ($f_t$), and maximum oscillation frequency ($f_{max}$). An additional result is that the SiGe HBT low-temperature performance is superior to that of the Si BJT [3].

Authors’ current addresses: T. D. England, C. Chatterjee, N. Lourenco, R. M. Diestelhorst, J. D. Cressler, School of Electrical and Computer Engineering, The Georgia Institute of Technology, 777 Atlantic Drive NW, Atlanta, GA 30332–0250, USA. E-mail: tengland3@gatech.edu. S. Finn, S. D. Phillips, E. W. Kenyon, Texas Instruments, 1700 Corporate Dr., #180, Norcross, GA 30093, Laleh Najafizadeh, Rutgers University, 96 Frelinghuysen Rd., #520, Piscataway, NJ 08854. Manuscript SYSAES-2013-0053, DOI. No. 10.1109/MAES.2014.130053, received April 10, 2013, and ready for publication November 20, 2013. Review handled by M. Jah. 0885/8985/14/ $26.00 © 2014 IEEE
As the SiGe HBT approaches cryogenic temperatures, the most important device metrics for circuit design improve: current gain, transconductance, $f_T$, $f_{MAX}$, and broadband noise [4]. Moreover, SiGe HBTs have been shown to be robust not only at 77 K but down to 300 mK [3]–[8]. Instead of expending size, weight, and power to keep electronic systems heated, designers can leverage the cold capability of the SiGe HBT to improve system metrics and operate robustly at cryogenic temperatures. Because the SiGe HBT is so well-suited for the low temperature regime it is easy to falsely assume it cannot be utilized at high temperatures; however, high temperature SiGe electronics are presently under development including a SiGe HBT-based voltage reference that has been demonstrated for operation up to 300°C [9]. Thus, the SiGe HBT has emerged as a viable contender for ultrawide temperature applications.

Additionally, the SiGe HBT has a natural, built-in resistance to total-ionizing dose and displacement damage (DD) radiation effects, both of which can be explained by aspects of the SiGe HBT device structure. First, the emitter-base spacer insulator is very thin (e.g., 100 nm) and importantly is contained within a heavily doped region of the epitaxial base, such that any interface damage is effectively confined by the high doping (the trap-induced modulation of the local space charge region cannot easily occur) and parasitic leakage is thus suppressed. Second, the base itself is very thin (e.g., 100 nm) and heavily doped, minimizing the effects of displacement damage. Finally, the shallow trench isolation in the collector-base junction is thin and located well away from the carrier transport path of the transistor—all from [10]. Experimental data has shown that newer generation SiGe HBT devices are hardened against major degradations in current gain in mid- and high-injection to multiple Mrad dose levels and have even higher TID tolerance at cryogenic temperatures [11]. The SiGe HBT therefore shows great promise in being the cornerstone of space electronics due to its robustness against temperature variation and tolerance to radiation exposure.

### APPLICATION

The transceivers presented in this work were designed as part of a larger NASA project “SiGe Integrated Electronics for Extreme Environments.” The project’s goal was to demonstrate that SiGe BiCMOS technology was a viable candidate for implementing extreme environment electronics, particularly targeting future missions to the moon and Mars [12]. This team used IBM’s SiGe 5AM process to create a library of circuit blocks of all types (analog, digital, RF, and mixed signal) and validated them over the expected Lunar temperature range (~180 to +120°C) as well as against both TID and single-event latchup (SEL) radiation damage [2], [13]–[17].

As a final proof of concept, the team designed the SiGe Remote Electronics Unit (REU), which consisted of two application-specific integrated transistors (ASICs), the Remote Sensor Interface (RSI) and Remote Digital Control (RDC). Contained within the RSI ASIC were a total of 16 instrumentation channels of three different types and a 16-channel, multiplexing, Wilkinson analog-to-digital converter. The second chip, the RDC, acted as the outside communication port and controller for the RSI, programming all gain, calibration, and sensor stimulus settings. Within the RDC two transceivers, one primary and one redundant, were the communications links. A system diagram of the final implementation of the transceivers is shown in Figure 1, including sensors, REUs, and a central system controller.

![Figure 1](https://example.com/fig1.png)

The transceivers are designed for the SiGe Remote Electronics Unit that can interface with up to 16 sensors simultaneously and operates over the same 90 K to 390 K temperature range after [18].
RS-485 TRANSCIEVER

TRANSMITTER DESIGN

The transmitter takes in a single-ended 3.3 V CMOS digital signal and translates it to a differential bus signal. The input signal is gated for an enable/disable operation then buffered to drive subsequent stages. An example RS-485 bus is shown in Figure 2. The output utilizes a BiCMOS gate topology for output drive capability as shown in Figure 3. A resistor is used to prevent current peaking in the lower 32 parallel HBTs improving the long-term reliability of the transmitter. Ballast resistors on the emitters of the upper HBTs serve to maintain even current density through each of the 32 parallel HBTs. Two such output stages are required, one for each side of the differential bus.

RECEIVER DESIGN

The receiver converts the differential bus signal back to a 3.3 V CMOS digital signal. Resistor networks at the inputs serve to improve the input common-mode range as shown in Figure 4. They are weighted in the positive direction to align with the n-type input differential pair. They are followed by active loads that wrap the signal around for rail-to-rail range into CMOS inverters that buffer the signal to the output. Hysteresis is provided by a polysilicon feedback resistance from the output of the differential pair back to base terminal of the positive side of the differential pair.

MEASUREMENT RESULTS

The transceivers were wirebond packaged inside 28-pin dual in-line packages (DIPs) in pairs because each one can only be...
enabled as either a transmitter or receiver. The room-temperature measurement shown in Figure 5 required high-speed, screw-on, low-loss SubMiniature version A (SMA) connectors to maximize the measurement bandwidth. The SMAs were connected through bias tees to the 50 Ω, high-speed oscilloscope ports on a Tektronix DPO71254. The transceivers performed robustly at 20 mbps.

Other DIPs were tested inside a cryogenic Dewar with coaxial conductors from 90 K up to 390 K with 50 K steps. One bus termination was located as close as possible to the transceiver, just outside the Dewar, and the other was placed near the oscilloscope for signal integrity. The bandwidth of the Dewar limited the overtemperature measurements to a speed of 2 mbps. Measurements were made with a Tektronix AFG3252 function generator and a Tektronix TDS7054 oscilloscope using the oscilloscope's built-in measurements of rise/fall time, propagation delay, and signal amplitude.

Figure 6A shows the propagation delay of the receiver and transmitter over temperature. The receiver was largely unchanged while the transmitter saw an improvement of about 2 ns at the lower temperature points.

Receiver—The receiver hysteresis was measured with an HP 4155 sweeping the positive side of the bus while holding the negative side at ground. The results are shown in Figure 6B. The hysteresis range monotonically decreases as temperature rises due to the temperature drift of the input and feedback resistor network.

Transmitter—Figure 7A shows the rise and fall time of the transmitter over temperature. The values tended to stay constant through most of the range except for one outlier in the fall time. Close to the upper bound, the values began to increase as the output transistor slowed. The measured output swing is shown in Figure 7B. The dip at bottom of the temperature range is the result of the $V_{BE}$ shift due to presence of fewer thermally activated carriers. The total change in swing is less than 150 mV or 5% of the average.
**RS-485 DIE PHOTO AND PERFORMANCE SUMMARY**

A die photo of the RS-485 transceiver is shown in Figure 8. It only occupies 575 µm × 375 µm of space without pads, which is less than 0.25 mm². A number of RS-485 transceiver performance parameters are shown in Table 1.

**ISO 11898 TRANSCEIVER**

**TRANSMITTER DESIGN**

The input stage of the ISO 11898 transmitter uses combinational logic rather than transmission gates to implement the enable/disable functionality. The change reduces the transmitter propagation delay and makes it simple to implement the high-impedance recessive state. The necessary data inversion compared to the RS-485 transmitter also takes place in the combinational logic.

The dominant ‘0’ condition of the ISO 11898 standard (dominant positive voltage on the bus itself) simplifies the output stage shown in Figure 9. Each side of the differential bus is only required to provide voltage/current drive in one direction, asserted only during the dominant condition. When recessive, the output presents a high impedance value. This implementation looks similar to the RS-485, but the output is split such that the positive side of the bus is only connected to the emitter ballast of the upper HBT array and the negative side of the bus is only connected to the collector of the lower HBT array. As with the RS-485 each HBT represents 32 devices. The bottom 32 devices share all nets. The devices in the top array share base and collector nets, but each has their own emitter ballast resistor that then shares the positive bus net.

**RECEIVER DESIGN**

The ISO 11898 receiver has a resistor-network input similar to the RS-485. Resistor value differences between the positive and negative differential inputs move the decision point from 0 V to between 500 and 700 mV to be compatible with the ISO 11898 standard. Additionally, the input sides are swapped to implement the data inversion from the bus.

**OVERTEMPERATURE MEASUREMENT**

The same overtemperature setup for the RS-485 was used for the ISO 11898 transceiver measurements. The hardware was at temperature in the dewar, but the data bus and terminations were at room temperature outside the dewar. Propagation delay was measured by passing data through the transmitter, onto the bus, and back through the receiver. Both the bus and the receiver output were monitored. Figure 10A dis-

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**Table 1. RS-485 Transceiver Performance**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transceiver max. data rate</td>
<td>&gt; 20 mbps</td>
</tr>
<tr>
<td>Receiver propagation delay</td>
<td>&lt; 19 ns</td>
</tr>
<tr>
<td>Receiver hysteresis range</td>
<td>&gt; 90 mV</td>
</tr>
<tr>
<td>Receiver current consumption</td>
<td>&lt; 3 mA</td>
</tr>
<tr>
<td>Transmitter propagation delay</td>
<td>&lt; 23 ns</td>
</tr>
<tr>
<td>Transmitter rise/fall time</td>
<td>&lt; 4 ns</td>
</tr>
<tr>
<td>Transmitter output swing</td>
<td>&gt; 2.9 V</td>
</tr>
<tr>
<td>Transmitter current consumption</td>
<td>&lt; 53 mA</td>
</tr>
</tbody>
</table>

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**Figure 8.**
Die photo of the RS-485 transceiver. It only occupies about 575 µm × 315 µm without pads.

**Figure 9.**
Schematic of the output stage of the ISO 11898 transmitter. Because it only provides drive in one direction, only one such stage is needed.
plays the measured values of propagation delay over temperature through the transmitter only and the transmitter and receiver together. This data representation adds the offset caused by the internal dewar cabling equally to both values. There was less than a 4 ns difference from the highest to the lowest temperature point caused by the increased speed of the devices at low temperatures.

**Receiver**—The ISO 11898 receiver hysteresis was measured with an HP 4155 sweeping the positive side of the bus while holding the negative side at ground. The results are shown in Figure 10B. Much like the RS-485, the hysteresis range monotonically decreases as temperature rises due to the temperature drift of the input and feedback resistor network. All values are acceptable for the final implementation of the receiver.

**Transmitter**—The rise and fall times of the transmitter output are shown in Figure 11A. They are dominated by the parasitic capacitance seen by the bus and are very consistent over temperature, varying less than 1 ns. Experiments were also conducted over cable length. The resulting rise time measurements are shown in Figure 11B. Even over the 50 ft bus, rise times were consistent across transmitter temperature, never changing more than 0.5 ns.

Finally, the output swing is shown in Figure 12. The output swing decreases by approximately 0.5 V over temperature from the increased $V_{BE}$ requirement of the output SiGe HBTs at lower temperatures. The overall value is lower than the RS-485 because of the unidirectional drive.

### TOTAL IONIZING DOSE EXPERIMENT

The total ionizing dose test was conducted at Crocker Nuclear Laboratory at the University of California, Davis [19]. Hardware was irradiated with 63 MeV protons. Samples were wire bonded into a DIP, soldered onto a printed circuit board and clamped in the beam line as shown in Figure 13.

Hardware was irradiated to three levels: 200 krad(SiO₂), 500 krad(SiO₂), and 2 Mrad(SiO₂). At each dose level, sam-

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**Figure 10.**

A. The ISO 11898 transceiver (operating at 800 kilobit per second) propagation delay is consistent over temperature, showing an approximate 3 ns change from the highest to lowest points. B. Hysteresis range for the ISO 11898 receiver operating over a 300 K temperature range. The change is due to the temperature drift of the resistance of the polysilicon on deep trench resistors used in the input and feedback network.

**Figure 11.**

A. The rise and fall times of the ISO 11898 transmitter (operating at 2 Mbps with 50 ft bus length) vary minimally over temperature, helping to ensure robust transition edges throughout the range. B. The rise time of the ISO 11898 (operating at 2 Mbps) is nearly constant over temperature with various bus lengths.
Cold-Capable, Radiation-Harden Wireline Tranceivers

Figures and Text:

Figure 12.
The output voltage swing of the ISO 11898 (operating at 800 kilobit per second) increases over temperature. It is approximately 1V lower than the RS-485 because of the unidirectional current drive.

Figure 13.
Photograph of the ISO 11898 transceiver sample setup for proton irradiation at Crocker Nuclear Laboratory.

Figure 14.
Percent change for various transceiver parameters versus total ionizing dose. The ISO 11898 transceiver at 63.3 MeV proton exposure is shown to be TID tolerant to 2 Mrad. Most parameters stay within 5% of their prerad values. The largest change stays within 15%.

Figure 15.
The basic form of the empirical models used for simulation of TID damage to the transceiver.

Text:

Samples were removed from the fixture, tested, and returned for further irradiation. Measurements were performed with a Tektronix AFG3252 function generator and a Tektronix TDS2012B oscilloscope. Much like the overtemperature measurement, propagation delay was measured from the transmitter input to the bus, and from the transmitter input to the receiver output.

Both the receiver and transmitter showed radiation hardness through 2 Mrad(SiO2) dose. Most of the measured specifications stayed within 5% of their prerad values. Even the falling- to rising-edge propagation delay of the transmitter varied less than 15% from nominal. The average percent changes of output swing and propagation delays are shown in Figure 14.

As a secondary check to the measured data, compact-model simulations were executed with empirical TID models. Device TID data provided by [11], [20], [21] were utilized to calibrate leakage current sources implemented in Verilog-A for circuit simulation, as shown in Figure 15.

Simulations modeled worst-case 540 krad radiation exposure of the nFETs and 1 Mrad exposure of the SiGe HBTs. Results showed similar trends as those seen in measurement. The measured and simulated changes are shown in Table 2. Measurable changes were in the same direction as simulation, and immeasurable changes were confirmed to be minimal in simulation.

BROAD-BEAM TESTING

The broad-beam heavy-ion experiment took place at Lawrence Berkeley National Laboratory’s Berkeley Accelerator Space Effects Facility. Three ion species from the 10 MeV/ nuc cocktail were used: O, Cu, and Xe. The resulting surface linear energy transfer (LET) values and approximate deposited charge along the ion path are shown in Table 3. A normal angle of incidence was used for all three ions. Xenon was the highest LET ion available in the cocktail and represents the practical worst case in heavy-ion-strike testing. Xenon strikes are extremely rare in actual space environments. For this experimental setup, the circuit was wire bonded onto a PCB that was mounted in the vacuum chamber in the beam line. Transient measurements were done with a Tektronix AFG3252 function generator and a Tektronix DPO71254.
high-speed oscilloscope with attached bias tees on the inputs to block the DC levels.

For the receiver tests, the negative side of the bus was grounded; the positive side was stimulated with a 1 MHz square wave, and the receiver output was monitored. The receiver exhibited numerous transients during Xe bombardment. Most transients peaked at the opposite output rail; i.e., when the output was at the ‘0’ voltage level, the transient voltage peak would be at the ‘1’ level and vice versa. An example is shown in Figure 16. This transient signature can be indicative of a sensitive CMOS inverter. Concordantly, the receiver output is buffered by a pair of CMOS inverters with large aspect ratios designed to drive the output pad. These devices are the largest in the receiver. It is reasonable to theorize that these inverters account for the most sensitive area in the receiver. In the final application, they will not be present, as the receiver output will be used by other on-chip circuitry, so in end-use conditions, the receiver could have notably higher tolerance to single-event effects. More investigation is needed to verify this claim.

During the transmitter tests, the transmitter input was stimulated with a 1 MHz square wave, and each side of the data bus was monitored separately. The shunt 50 Ω oscilloscope impedance on each side of the data bus caused excessive over- and undershoot of the transmitter signal switching to the high-impedance recessive bus state. It limited the minimum detectable transient in that state to 320 mV overshooting the steady-state value or 130 mV undershooting it on each side of the differential bus. It should be noted that transients below this threshold would not result in data disruption in the ISO 11898 communication standard. Switching to the dominate state was unaffected.

The transmitter proved to be tolerant against single-event transients. Irradiation with O ions produced no measurable transients on the data bus in either state. Cu and Xe ions did produce measurable transients on the single-ended bus voltages; however, the transients had minimal effect on the differential bus voltage. Figure 17 shows a typical transmitter transient from the highest LET ion, Xe. The resulting transient results in an almost purely common-mode signal that would be rejected by receivers on the bus. The differential component peaks at 56 mV, over an order of magnitude lower than the voltage necessary to cause an upset.

![Figure 16](image_url)  
**Figure 16.**  
A measurement of a typical Xe strike of the ISO 11898 receiver. The strike results in a transient pulse with a peak on the opposite rail, possibly indicative of a CMOS inverter. The large buffers driving the output pad are theorized to be responsible for these transients.

![Figure 17](image_url)  
**Figure 17.**  
A measurement of bus voltage deviation from DC during a typical Xe strike of the ISO 11898 transmitter. The strike results in a signal with a mostly common-mode component. Neither the common mode nor the differential component is large enough to disrupt data on an ISO 11898 bus.
Technology computer-aided design (TCAD) simulations were used to confirm the broad-beam results. A three-dimensional TCAD model of the IBM 5AM SiGe HBT was developed and is shown in Figure 18. The model was calibrated to the devices of the same size as those used in the transmitter. Simulations modeled a Xe ion strike into the center of the emitter stack of the device at the four unique bias points expected in the transmitter. The results of one of the simulations are shown in Figure 19A. As is normal, the collector and emitter currents were the largest and exhibited opposite polarity. These simulated strike currents were then used in corresponding current injection simulations of the transceiver.

To execute the current injection simulations, ideal current sources referencing the results of the TCAD simulations were placed between the terminals of a transistor to mimic the effects of a strike on that device. The simulation setups covered strikes on each of the two transmitter output devices at each of the two circuit states. The differential bus voltage variation from each of the four situations can be seen in Figure 19B.

The simulations confirmed the broad-beam measurement result: the ion strikes result only in nondisruptive signals. In all cases, the differential transients have positive peaks, which would have no effect in the case of an ‘1’ output from the transmitter because the differential voltage would already be positive. In the cases where the transmitter has a ‘0’ output, the maximum differential peak is less than 100 mV, approximately an order of magnitude less than the necessary swing to cause a data transition (bit upset). The transmitter is shown to be hardened against these single-event effects even at LETs near 60 MeV·cm²/mg.

ISO 11898 Die Photo

A die photo of the ISO 11898 transmitter is shown in Figure 20. It only occupies 320 µm × 330 µm of space without pads, which is less than 0.110 mm².

Summary

Electronics in space-based systems are in the process of a paradigm shift moving from centralized, heavily shielded, temperature-controlled warm boxes to distributed, minimally shielded sensing and control nodes. SiGe BiCMOS technology is one of the enablers of this move with its ability to withstand extremely wide variations in temperature and high radiation doses. This article has presented two SiGe BiCMOS wireline transceivers designed to be a part of the new system perspective by creating a means of control and communication across vehicle-wide buses. Both the RS-485 and ISO 11898 transceivers have been shown to work robustly from 90 K to 390 K, with consistent rise/fall times, propagation delays, and output amplitudes. Additionally, the ISO 11898 transceiver is
Figure 20. 
Die photo of the ISO 11898 transmitter wire bonded for over-temperature measurements. It only occupies 320 µm × 330 µm without pads.

TID tolerant to 2 Mrad, and the transmitter is hardened to single-event effects. ◆

ACKNOWLEDGMENTS

This work was supported by NASA ETDP under contract NNLO6AA29C. We are grateful for the support of A. Keys, M. Watson, D. Frazier, M. Beatty, D. Hope, and C. Moore of NASA; E. Kolawa of JPL; A. Joseph, T. Lamothe, and the IBM SiGe development team; and R. Berger, A. Mantooth, M. Barlow, A. Authors, C. Lee, and the other member of the SiGe ETDP team for their contributions.

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