

Radiation Tolerant CAN Transceiver for Space

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Abstract – To fully exploit the advantages of the CAN bus for space a radiation tolerant CAN transceiver on a space ASIC technology is required to realize the integration of the interface and application in a single integrated circuit. The feasibility of realising a CAN interface in a standard digital radiation tolerant CMOS technology has been investigated. The lack of high-voltage devices and high current diodes as well as the low 3.3V operating voltage of the process makes the compliance to the CAN bus severe -2V to 7V common-mode range and -3V to 16V failure tolerance voltage difficult to realise. However by spreading the bus voltage over several transistors and monitoring the bus voltage as well as current, failsafe operation can be realised. The architecture of such a CAN transceiver has been realised and implemented in the DARE180U technology. The transceiver has been electrically and radiation tested and found to be compliant to the space CAN standard. The radiation tests demonstrated a low cross-section for both the receiver and transmitter and demonstrated voltage tolerance up to 16V.

Keywords—CAN, wireline, bus, transceiver, high-voltage circuit, voltage extension, CMOS, space, radiation.

I. INTRODUCTION

In the latest years a trend towards modularity, reuse and versatility of on board avionics is accelerating. As a consequence, most of the analogue acquisition electronics are “pushed away” from the On Board Computer (OBC) and treated as much as possible at peripheral unit's level. We can foresee future systems where the use of 'legacy' discrete spacecraft interfaces as described in the ECCS-E-ST-50-14C standard [1], like discrete telemetry, PPS as well as most of the direct ON/OFF commands are replaced by the CAN bus.

This makes extensive use of CAN bus interface capabilities, like in modern automotive powertrain systems or distributed industrial controls, possible. The exploited capabilities are:

- High availability: if a control unit fails, the rest of the system must continue to be functional as far as possible in order to exchange information.
- High data density: all control units have the same information status at all times. This means there is no difference in data between the control units. In case of faults anywhere in the system, all the connected users can be informed with equal certainty.

Since the transmission of a CAN message may be initiated by any node of a system (multi-master capability) as soon as

the bus is idle, any node of the system may exchange information with any other node. This feature is very important because it very efficiently supports event-oriented message transmission.

II. CAN FOR SPACE

Recognizing CAN maturity and popularity, several European space missions have already adopted the CAN Bus on their spacecrafts, subsystems or payloads. So far the benefits of CAN bus have been mostly exploited in payload busses, due to the limited availability of recurrent units (like AOCS sensors) mounting CAN interface.

These experiences have prompted ESA to drive a standardization process resulting in recommendations to extend the CAN bus and CANOpen specification to cover aspects that are required to satisfy special needs that have been identified as being commonly required on-board spacecraft.

The very extensive experience of the use of CAN bus in terrestrial applications, such as automobiles and factory process control, often in applications that have demanding safety and reliability requirements, and operate in hostile environments that have similarities to spacecraft on-board applications, have been taken into account when issuing the standard for the use of the CAN bus in space, ECSS-E-ST-50-15C [2]. It baselines the ISO 11898 Physical layer as preferred solution for spaceborne CAN networks.

The availability of Low Voltage Rad-Hard CAN transceiver will allow more future mission to benefit from the additional features provided by CAN, furthermore reducing European dependence on interface drivers (RS-485, MIL-1553) coming from US manufacturers.

Given that the number of nodes that can be supported by the CAN bus and sub-branches is a ten to hundredfold larger than for the MIL-BUS-1553, the customary separation between transceiver and application integrated circuit may not longer convenient from cost and application printed circuit board area considerations. Therefore an integrated circuit with both application circuit and CAN interface has to be contemplated.

The CAN bus, as defined by the physical layer standard ISO 11898-2 [3], consists of a 120 Ohm CAN H and L differential bus that is terminated at both ends by 120 Ohm onto which the multiple CAN node transceivers are attached. The bus knows two states “recessive” and “dominant” through which communication between the nodes takes place. The

recessive state has both lines around a 2.5V potential, while for the dominant state the differential voltage between the lines is increased to above 1.5V. Common-mode variations on the CAN H and L lines are specified to range from -2V to 7V. In addition during a fault condition the lines could be shorted to supply or ground and thus extend the input voltage range of the H and L CAN ports, for which the transceiver should operate from -3V to 16V. For proper operation of the bus the H and L input impedance should be less than 10kOhm and match within 3%.

The application circuit attached to the interface dictates a nominal supply voltage of 3.3V and for space should ensure fail-safe operation. The latter implies that in case of a failure like a short or open of the CAN H and L lines, no failure propagation should take place. This could occur either through the erroneous reception or transmission of data in case of an open circuit, the burn-out of the driver in the case of a short to ground or the reverse powering of the integrated circuit through the CAN ports for shorts to higher supply voltages. Therefore the architecture of the CAN transceiver on the integrated circuit should not only comply to the CAN standard in radiation environment, but should also guard against failure propagation. These and additional constraints on the operation of the CAN bus in space are stipulated in the space standard [2].

In the following sections (i) the CAN transceiver architecture is presented, (ii) the implementation of the transceiver circuit is discussed, (iii) the electrical measurement results on the CAN transceiver are shown and (iv) the radiation test results on the CAN transceiver presented.

I. ARCHITECTURE

A. Technology

The fail-safe operation of the CAN transceiver requires tolerance to high voltages and the prevention of reverse powering through the bus ports. The customary solution to these requirements is through the selection of a power integrated circuit technology that supports high voltage transistors and high current diodes. The former ensures high voltage tolerance, while the latter operation at 3.3V without reverse powering. For the commercially available devices the most typical implementation for the driver are shown in Figure 1. The high voltage transistor ensures tolerance to the high common-mode voltage range and shorts to higher supply voltages. The high current diodes ensure that the 1.5V differential voltage can be achieved in the dominant state in presence of a double diode voltage drop from a minimum 3V supply.

For space digital CMOS integrated circuit technologies are well established and suitable for the space applications at hand. The availability of high voltage transistors and high current diodes is less common for space integrated technologies and should therefore not be relied upon in the realisation of a CAN transceiver for space. As baseline the DARE180U technology is chosen to demonstrate that the developed CAN transceiver can be realized on most comparable space technologies.

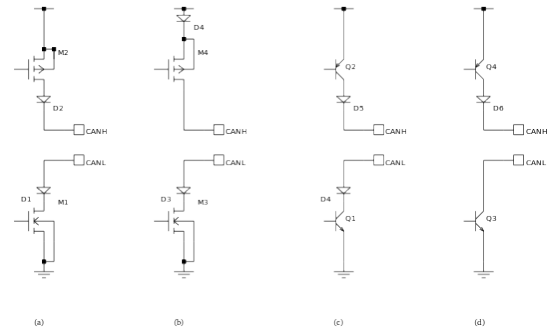


Figure 1. Commercial Transmitter Implementations

B. Architecture

The high voltage tolerance is realised in the selected technology through the stacking of transistor floating in their well such that each of them remains within its safe operating voltage range. The implementation of the driver circuit is further discussed in section II.

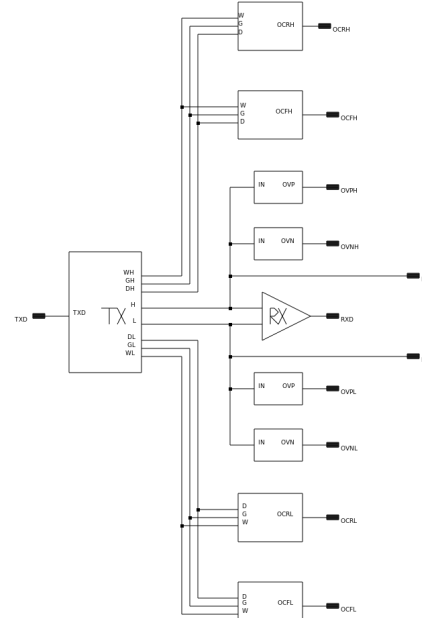


Figure 2. CAN Transceiver Architecture showing the transmitter, receiver and protection circuits for over-current in the forward as well as the reverse direction and for over-voltage conditions.

The fail-safe operation of the CAN driver and receiver requires additional support circuitry that detects the existence of open and shorts on the CAN bus lines, such as to protect the operation of the CAN transceiver. In particular the driver has to be protected against (i) reverse leakage and powering, (ii) high currents and (iii) over-voltages. This can be realised with the reverse current, over-current and over-voltage detectors as shown in Figure 2.

While these detectors monitor and protect the CAN driver from shorts, they can not completely determine the state of the CAN bus. In particular the existence of open circuits is not detected. For these the bus differential voltage and transceiver port currents have to be sampled at the end of a dominant

transmission period. In particular the bus differential voltage, CAN H and L port undercurrent as well as a CAN H and L port current imbalance has to be detected.

The complete state of the CAN bus can now be determined from these 8 detection measures; the H and L port forward and reverse over-current detectors, the H and L port over-voltage detectors, the H and L under-current detector, the H and L sampled current unbalance detector and the H and L bus sampled voltage differential voltage.

II. IMPLEMENTATION

A. Receiver

For the receiver the large input range from 7V to -2V must be compressed into a smaller 3V supply voltage range, with the removal of the common-mode signal. Detection of the dominant bus state should occur for differential bus voltages above 1.2V, while the recessive state is identified for differential bus voltages below 500mV. For a differential threshold voltage of 900mV and 50mV hysteresis the receiver would be compliant to the standard. In reducing the signal input range, the signal to noise ratio should not be compromised in order to maintain the high noise and spurious immunity figures.

B. Transmitter

With only a limited 3.6V source to drain, source to gate, gate to drain and gate to well voltage allowed in a Mixed-Mode 180nm CMOS technology with 350nm devices, the output driver devices have to be stacked to limit the voltages across its terminals. The driver output stage is shown in Figure 3. The resistor string ensures that in the recessive state the voltage across the devices is always less than 3.6V, irrespective of the CAN H or CAN L port voltage. The output stage specific pre-driver is not shown in Figure 3 and will be the subject of future publication [4].

Reverse leakage in the recessive state is limited by sharing the wells between pairs of devices near the port and biasing it from the mid voltage via a resistor. The resistor ensures that for port voltages outside the supply voltage range no excessive leakage occurs through the forward bias wells. With this construction the CAN H bus line can be lifted above the supply rail and the CAN L bus line below ground level.

Given the recessive state port voltage levels between 2V and 3V, the minimum supply voltage level feasible is 3.3V, with a minimum voltage of 3.0V and maximum of 3.6V. For this voltage the minimum differential voltage between the CAN H and L ports in the dominant state should be 1.5V over all the temperature, voltage and process manufacturing conditions.

The minimum CAN H port voltage should according to the space CAN standard [1] should be 2.75V. Given the minimum supply voltage of 3.0V, the lower mobility of the PMOS transistors and that ideally the PMOS pull-up and NMOS pull-down string should be as much as possible symmetrical to realize impedance matching, a minimum 2.35V voltage appears feasible. Commercial 3.3V CAN transceiver devices indicate a minimum of 2.45V.

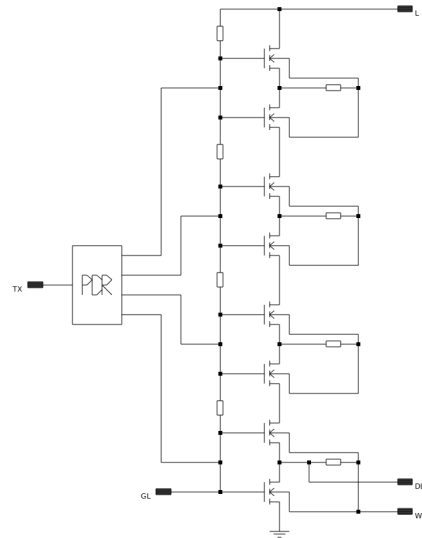


Figure 3. CAN Transmitter

The choice of the recessive voltage level and of the individual CAN_H and CAN_L port voltage in the dominant state should take EMC issues into account. Minimum EMC emissions occur when equal voltage swings in opposite directions are achieved for the CANH and CANL ports. The recessive voltage levels should be within the 2V to 3V range to realize compatibility with older devices and prevent too large a DC current to flow between the nodes at different recessive voltages. Striving for an equal voltage swing for both CAN_H and CAN_L port of 750mV, this leads to the choice of the recessive port voltage around voltage 2.1V, a dominant CAN_H port voltage of 2.85V and CAN_L port voltage of 1.35V. However the inclusion of margin against manufacturing variations, supply voltage, temperature and the constraint to keep the port impedances equal to within 3%, leads us to the following choice of target port voltages; recessive port voltage 2.2V, dominant CAN_H port voltage 2.75V and CAN_L port voltage 750mV, with a dominant differential voltage of 1.9V.

C. Forward over-current detector

In case the CAN_H or L port is shorted to ground or supply too large a current can flow in the dominant state through the transmitter driver circuit, which could damage the integrated circuit through over-heating. To circumvent this problem the current through the driver can be measured and compared with the acceptable maximum current. For the CAN_H port the current is measured by applying the same drain, gate and drain voltages to a smaller copy of the transistor used in the driver of the transmitter and measuring the current. The implemented circuit is shown in Figure 4. For the CAN_L port a complementary circuit is implemented to detect over-current due to shorts of the CAN_L port to positive (up to 16V), supply voltages.

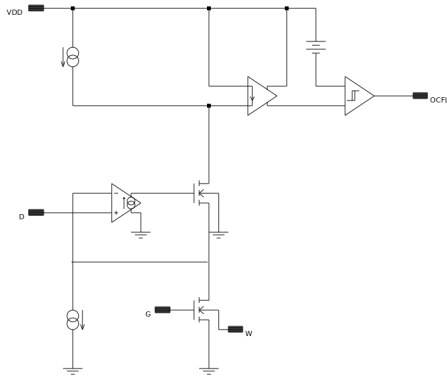


Figure 4. Forward CAN L driver over-current detection circuit

D. Reverse over-current detector

As for the forward over-current detector a large current can flow through the transistor of the driver of the transmitter in the dominant state when the CAN H port is shorted to a higher (up to 16V) supply voltage or the CAN L port is shorted to the lower supply voltage (down to -3V). The current flows than through the transistor in the reverse sense and correspondingly a reverse current copying circuit has been created. Again the drain, gate and source voltage of the transistor of the driver of the transmitter are applied to a smaller version whose current is measured. The circuit is shown schematically in Figure 5.

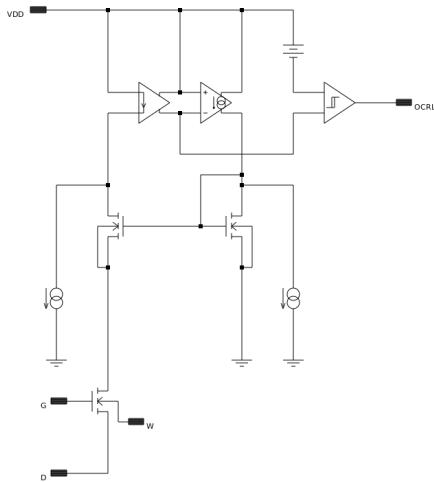


Figure 5. Reverse CAN L driver over-current detection circuit

E. Over-voltage detector

In case that the bus voltage is shorted to a voltage above 16V or below -3V and the transmitter in recessive state, excessive in-rush currents could occur when switching the transmitter to the dominant state. To avoid the occurrence of such events an over-voltage detector is implemented. The circuit is realized with a simple voltage divider attached to each of the state, whose output is compared with a reference voltage.

F. Sampled under-current detector

At the end of the dominant period the current through the H and L port should be about $1.5V/60\Omega = 25mA$. Failure to reach this current is indicative of an open or short on the CAN bus lines. The forward current copying circuit is reused for this detector to determine the current in both the H and L ports at the end of the dominant period. In case deviations occur an alarm is raised.

G. Sampled current unbalance detector

Towards the end of the dominant state the current out through the H port should match the current going into the L port. A mismatch between these currents is indicative that a weak short or open circuit exists on the CAN bus. The current unbalance detector re-uses the smaller copy of the port currents to determine the mismatch between the H and L port at the end of the dominant period.

H. Sampled under/over voltage detector

Lastly in the absence of arbitration the CAN bus voltage should be in excess of 1.5V to ensure compliance to the CAN bus standard. Measured voltage above or below indicate the existence of the short or open circuit on the CAN bus lines. This detector samples the voltage at the end of the dominant period and compares it with given threshold voltages. Deviations from the 1.5V trigger an alarm.

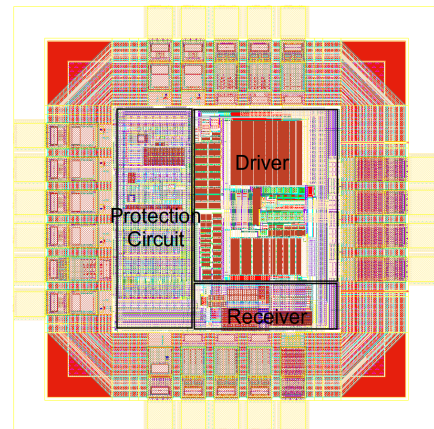


Figure 6: Layout and Chip photo of CAN Transceiver

I. Implementation

The CAN transceiver as described with the forward and reverse over-current and over-voltage detectors for both ports has been realized on DARE180U radiation tolerant technology. The layout of the transceiver and chip photo is shown in Figure 6 and the chip photo in Figure 7. The driver, receiver and transceiver protection circuits are indicated.

III. MEASUREMENT RESULTS

The transceiver has been manufactured and tested over temperature and with radiation. Measurements have been carried out to determine the receiver input threshold and hysteresis, the transmitter output levels as well as the transceiver current consumption, port impedance, propagation

delay and high-voltage resilience. Figure 8 shows the CAN transceiver in loop back configuration operating at 200kbit/s, successfully transmitting and receiving.

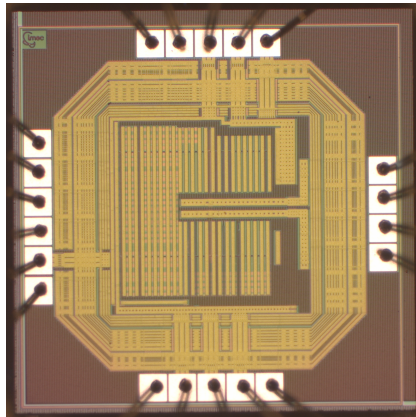


Figure 7: Chip photo of CAN Transceiver

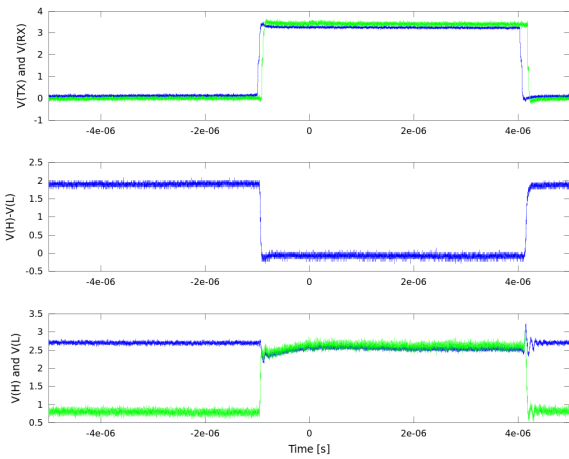


Figure 8 CAN transceiver signals at 200kbit/s

A. Receiver – Threshold, Hysteresis

The input receiver threshold levels for recessive to dominant and dominant to recessive transitions have been measured over a supply voltage range from 3.0V to 3.6V and over a temperature range from -55C to 125C. Over the whole supply and temperature range the hysteresis is maintained. The standard imposed transition levels for dominant at 900mV and recessive at 500mV are adhered to.

Description	Symbol	Unit	Min	Typ	Max
RX Threshold: D->R	$V_{diff,TH,RD}$	V	557	684	782
RX Threshold: R->D	$V_{diff,TH,DR}$	V	630	750	843
RX Hysteresis	V_{HYS}	mV	48	66	88

Table 1, Receiver measurement results

B. Transmitter – Output levels

The output levels have been measured over a supply voltage range from 3.0V to 3.6V and over a temperature range from -55C to 125C, with as typical condition 25C and 3.3V.

The dominant CANH port voltage, and recessive CANH, CANL port voltages are slightly lower than expected, probably due to additional parasitic track resistances.

Description	Symbol	Unit	Min	Typ	Max
CANH Dominant	$V_{CANH,D}$	V	2.340	2.668	3.012
CAN L Dominant	$V_{CANL,R}$	V	0.587	0.693	0.879
CANH Recessive	$V_{CANH,R}$	V	1.991	2.196	2.404
CANL Recessive	$V_{CANL,R}$	V	1.989	2.195	2.403
Dominant Differential	$V_{diff,D}$	V	1.538	1.973	2.379
Recessive Differential	$V_{diff,R}$	V	0.001	0.001	0.001

Table 2, Transmitter measurement results

C. Transceiver – Current consumption, Port impedance, Propagation delay

The current consumption has been measured over a supply voltage range from 3.0V to 3.6V and over a temperature range from -55C to 125C, with as typical condition 25C and 3.3V. The port input resistance and capacitance as well as the loop delay has been measured for typical conditions.

Description	Symbol	Unit	Min	Typ	Max
Current Recessive	I_R	mA	2	3	4
Current Dominant	I_D	mA	29	37	45
Input resistance	R_{in}	Ω		22	
Input resistance matching	M_{in}	%			1
Differential input resistance	R_{diff}	Ω		22	
Input capacitance CANH	$C_{in,CANH}$	pF		3.5	
Input capacitance CANL	$C_{in,CANL}$	pF		3.5	
Differential input capacitance	C_{diff}	pF		3.8	
Propagation Delay CMOS -> CAN: R -> D	$t_{TX,RD}$	ns	70	90	115
Propagation Delay CMOS -> CAN: D -> R	$t_{TX,DR}$	ns	30	35	40
Propagation Delay CAN -> CMOS: R -> D	$t_{RX,RD}$	ns	20	25	30
Propagation Delay CAN -> CMOS: D -> R	$t_{RX,DR}$	ns	25	30	45
Propagation Delay Loop R -> D	$t_{LOOP,RD}$	ns	100	120	140
Propagation Delay Loop D -> R	$t_{LOOP,DR}$	ns	60	65	75

Table 3, Transceiver measurement results

D. Transceiver – High voltage tolerance

The CANH port has been connected in its recessive state with a 1kΩ resistance to a voltage in excess of 16V for 24 hours without any noticeable changes in post-stress performance.

IV. RADIATION MEASUREMENT RESULTS

A. CAN transceiver – Radiation low-voltage SEE Sensitivity

Low voltage bias radiation tests have been carried out on the CAN transceiver at the LNS facility in Catania. The ions, angle, temperature used as well as the LET and fluence obtained are summarized in table 4.

Ions	Angle [deg]	LET [MeVcm ² /mg]	Fluence [cm ⁻²]	Temp. [C]	Bias [V]
Ar-40	0	6.4	1 x10 ⁷	40	2.1
Kr-84	0	24.0	1 x10 ⁷	40	2.1
Xe-129	0	49.0	1 x10 ⁷	40	2.1
Xe-129	45	72.1	1 x10 ⁷	40	2.1

Table 4: Low-voltage radiation test parameters

The bias voltage is shown in the electrical test set-up diagram in figure 9. It is the voltage of the voltage source that lifts the CANL line via a 1kOhm resistor to the bias supply voltage.

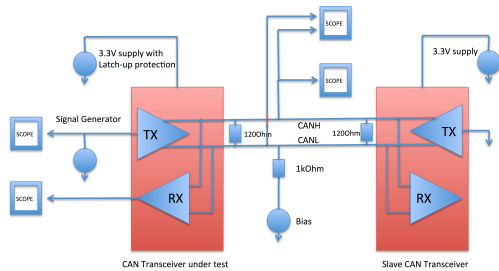


Figure 9 Electrical diagram of the radiation test set-up.

No SEL, SEB and SEGR radiation events have been detected. However radiation SET have been observed in the driver and receiver in the form of single bit errors. The combined receiver and transmitter cross-section are summarized in table 5.

LET [MeVcm ² /mg]	RX+TX cross-section [cm ²]
6.4	4.5 x10 ⁻⁷
24.0	1.5 x10 ⁻⁵
49.0	2.8 x10 ⁻⁵
72.1	3.3 x10 ⁻⁵

Table 5: Combined CAN receiver and driver measured SET radiation cross-section

Further analysis of the data shows that the cross-section for the driver is very much smaller than that of the receiver., such that the performance of the device can be significantly improved with a straight forward TMR implementation of the receiver.

B. CAN Driver – Radiation high-voltage SEE Sensitivity

High voltage bias radiation tests have been carried out on the CAN driver at room temperature at the GANIL facility in Caen. The ions, angle, temperature used as well as the LET and fluence obtained are summarized in table 6. A picture of the radiation test-setup is shown in figure 10.

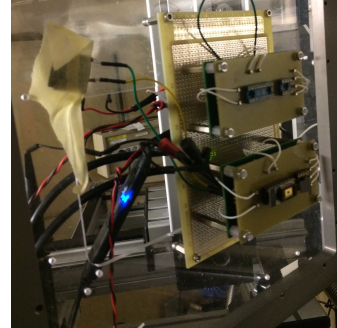


Figure 10 Radiation test set-up.

Ions	Angle [deg]	LET [MeVcm ² /mg]	Fluence [cm ⁻²]	Temp. [C]	Bias [V]
Xe-136	0	61.02	1 x10 ⁷	25	2.0
Xe-136	0	61.02	5 x10 ⁶	25	5.5
Xe-136	0	61.02	5 x10 ⁶	25	7
Xe-136	0	61.02	5 x10 ⁶	25	10
Xe-136	0	61.02	1 x10 ⁷	25	16.0
Xe-136	0	61.02	1 x10 ⁷	25	22.5

Table 6: High-voltage radiation test parameters

The actual CANH and CANL line voltage is lower than the bias voltage due to the input impedance of the driver ports. The measured CANH line voltages in recessive state for the different bias voltages are given in table 7.

Bias [V]	CANH Voltage [V]
2.0	2.2
5.5	4.0
7	6.5
10	9.2
16.0	14.0
22.5	16.0

Table 7. Recorded CANH lines voltages in recessive state as a function of applied bias voltage.

For each of the applied bias voltages no SEB, SEGR and SEL has been observed during the radiation test. It can be concluded that the driver circuit is robust in the presence of radiation. The observed SET on the receiver and driver are shown in figure 11 and 12 respectively. No significant increase of SET cross-section has been observed with increasing port common-mode voltage. Furthermore all SETs observed appear to last only a fraction of the transmission period and consequently are not expected to impact the data communication. Further BER tests should be performed to confirm this behaviour.

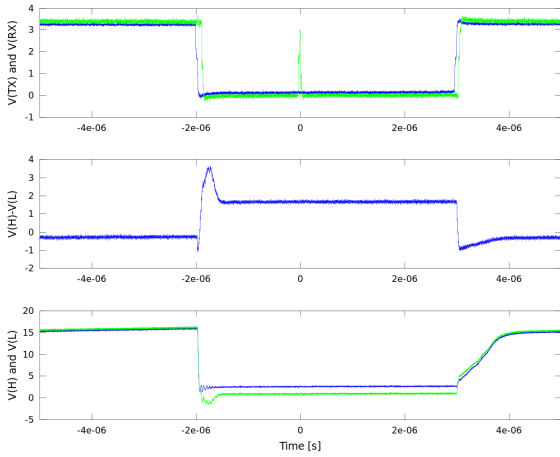


Figure 11 RX SET shown for the CAN transceiver signals at 200kbit/s with a 16V CM signal.

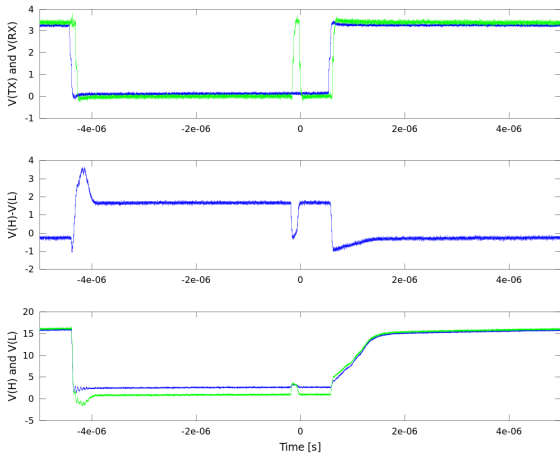


Figure 12 CAN transceiver signals 200kbit/s with a SET in the TX circuit with a 16V CM signal.

V. CONCLUSION

A CAN transceiver circuit has been implemented in the DARE180U technology with 350nm multi-well MOS transistors and tested over temperature and radiation. Aside from the CANH port output level in the dominant state the implemented CAN transceiver is found to be compliant to the CAN standard and radiation tolerant.

ACKNOWLEDGMENT

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