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Implementation of a Si/SiC Hybrid Optically Controlled High-Power Switching Device

Prashant Bhadri
University of Cincinnati

Kuntao Ye
University of Cincinnati

Elena A. Guliants
University of Dayton, eguliants1@udayton.edu

Fred R. Beyette Jr.
University of Cincinnati

Implementation of a Si/SiC Hybrid Optically Controlled High Power Switching Device

P. Bhadri, K, Ye, E. Guliants and F. R. Beyette Jr*

Photonic Information Processing Laboratory
Department of Electrical & Computer Engineering
and Computer Science
University of Cincinnati

ABSTRACT

The ever-increasing performance and economic requirements placed on commercial and military aircraft are resulting in the need for very complex avionic systems. To help alleviate some of the design complexity, fiber optic components have been suggested as an enabling technology that could allow the creation of an optical communications network routed throughout the avionic systems of an aircraft. Based on the often-cited benefits of high data throughput, immunity to EMI, reduced maintenance costs and reduced weight, the use of fiber optic links to communicate control signals and sensor information throughout the aircraft could lead to significant performance improvements for next generation aircraft. Fly-by-Light systems that use optical control signals to actuate the flight surfaces of an aircraft have been suggested as an important technology for avionic systems where degradation of signal integrity due to EMI can have catastrophic consequences. Current fly-by-light systems are limited by the lack of optically activated high-power switching devices. The challenge has been the development of an optoelectronic switching technology that can withstand the high power and harsh environmental conditions common in a flight surface actuation system. Wide bandgap semiconductors such as Silicon Carbide offer the potential to overcome both the temperature and voltage blocking limitations that inhibit the use of Silicon. Unfortunately, SiC is not optically active at the near IR wavelengths where communications grade light sources are readily available. Thus, we have proposed a hybrid device that combines a silicon based photoreceiver module with a SiC power transistor. When illuminated with a 5mW optical control signal the silicon chip produces a 15 mA drive current for a SiC Darlington pair. The SiC Darlington pair then produces a 150 A current that is suitable for driving an electric motor with sufficient horsepower to actuate the control surfaces on an aircraft. Further, when the optical signal is turned off, the SiC is capable of holding off a 270 V potential to insure that the motor drive current is completely off. We present in this paper the design and initial test results from a prototype device that has recently been fabricated.

Keywords: Optically Controlled Switch, Silicon Carbide Devices, High Power Switching

1. INTRODUCTION

Over the last two decades, fiber optic technologies have been an active research topic in government and industrial research laboratories around the globe. In addition to having a major impact on the telecommunications industry, the often-cited benefits of high data throughput, immunity to EMI and reduced weight and maintenance costs have driven the effort to incorporate fiber optic components into the flight control systems of modern commercial and military aircraft.[1,2] Currently, the development of these so-called Fly-by-Light systems is limited by the lack of optically activated high power switching devices.

Switching devices based on wide bandgap semiconductors (ex. Silicon Carbide) are know to have higher breakdown voltages than common semiconductors (i.e. Silicon and Germanium).[3] Further, SiC devices exhibit stable operation at elevated operating temperatures.[4] Thus, Silicon Carbide transistors have been suggested as possible switching devices for high power applications.[5] Unfortunately, SiC is not optically active at the near IR wavelengths where communications grade light sources are readily available. Thus, a hybrid approach is proposed that combines a silicon photoreceiver module [6-8] with a SiC power transistor. The Silicon Chip consists of a photodetector, a receiver circuit

* Correspondence: Email: beyette@ececs.uc.edu; Telephone: 513 556 4588; Fax: 513 556 7326 Mail: Dept. of ECECS, University of Cincinnati, PO Box 210030, Cincinnati, OH, 45221-0030, USA

and diagnostic circuits for real time evaluation of the control system operation. An analysis of the silicon chip design indicates that less than 5mW of optical signal is required to activate the silicon chip. When illuminated with the 5mW optical control signal the silicon chip produces a 15mA current that is used to drive a SiC Darlington pair. With a 15mA input current, the SiC chip will produce a 150 A current suitable for driving an electric motor with sufficient horsepower to actuate the control surfaces on an aircraft. In this paper we will report on our recent efforts towards demonstration of this hybrid Si-SiC module.

2. SMART OPTICALLY ACTIVATED HIGH POWER CHIP: DESIGN, SIMULATION AND PERFORMANCE

2.1. Silicon Carbide Device

As shown in Table 1, Silicon Carbide has a significantly higher breakdown field strength compared to other common semiconductors. Similarly, the thermal conductivity of is larger. Perhaps most importantly Silicon Carbide electronic devices have been shown to provide reliable operation at temperatures up to 600 °C. Hence the complexities of providing a heat sink can be avoided yielding electronic subsystems with dramatic weight reduction.

Properties	Si	GaAs	6H SiC
Band gap (eV)	1.1	1.42	3.0
Breakdown Field (MV/cm) @ 10^{17}	0.6	0.6	3.2
Electron Mobility (cm^2/V-s) @ 10^{16}	1100	6000	370
Saturated Electron Drift Velocity (cm/s)	10^7	10^7	2×10^7
Thermal Conductivity (W/cm-K)	1.5	0.5	4.9
Hole Mobility (cm^2/V-s) @10^{16}	420	320	90

Table 1. Comparison of Properties of Silicon, Gallium Arsenide and Silicon Carbide

2.2. 2.2 Limitation of the Silicon Carbide Approach

Like Si based devices, Silicon Carbide is an optically active material that enables the development of fly-by-light avionic systems. An optically activated SiC device was originally considered as the sole component for an optically controlled high power switch. As suggested by figure 1a), simulation of a single SiC bipolar transistor shows that the input signal power required to source 150 A is approximately 5 Watts. With common solid-state light sources producing optical powers in the range of a few hundred mW, a 5-Watt optical power requirement is too large for practical consideration.

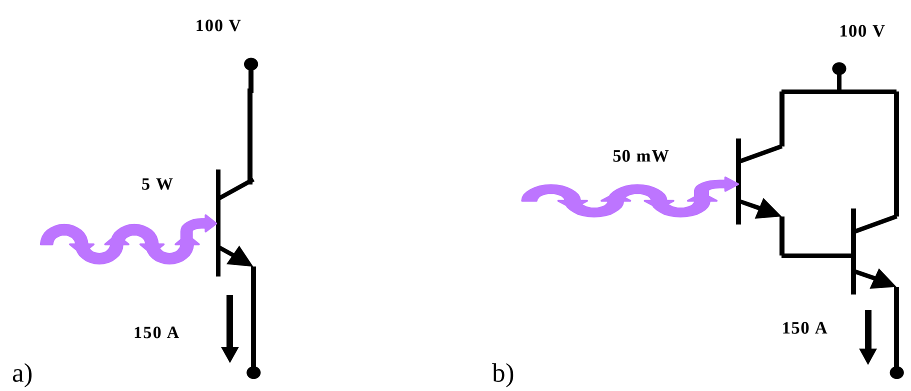


Figure 1 a) Single SiC transistor requiring 5W optical signal to produce a 150A drive current. b) a SiC Darlington Pair used to reduce the input optical power requirement to 50 mW.

Figure 1b) shows an alternative approach where a Darlington configuration is used to significantly reduce the optical power requirement. Initial simulations predict the optical power requirement could be reduced to the ~50 mW. While this approach reduces the optical power requirement to a practical level, it cannot address a fundamental problem faced by SiC optoelectronics. Unfortunately SiC is only responsive at optical wavelengths less than 420nm. Thus it is transparent in most of the Visible and all of the Infrared regions of the optical spectrum. As a result it's not compatible with 835nm optical control signals and the existing WDM technology.

3. CURRENT APPROACH USING SILICON – SILICON CARBIDE HYBRID

To address the difficulties described above, we have proposed a single hybrid device package that integrates a "smart" silicon photoreceiver chip with a SiC Darlington pair that is capable of providing the high power switching characteristics needed to drive an electric motor. With this approach a silicon photodetector can easily be designed that is active in the visible and near infrared regions of the optical spectrum. Additionally, compatibility issues are significantly reduced by replacing the optical SiC input with an electrical signal. Figure 2 shows the hybrid device in block diagram form.

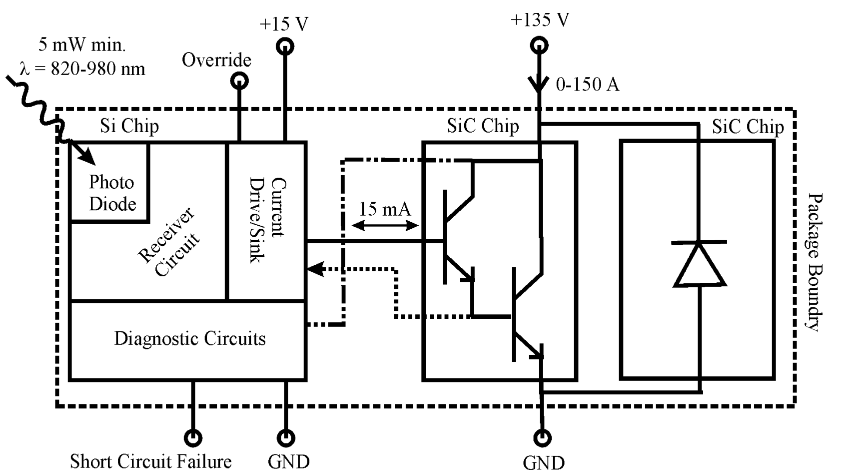


Figure 2 Block diagram of the Si/SiC hybrid device package showing the smart silicon chip functional blocks, the SiC Darlington pair and a SiC Fly-back diode.

As shown in Figure 2, the smart silicon chip consists of photodiode, receiver circuit, current drive/sink circuits and diagnostic circuits. The silicon chip drives the SiC Darlington pair with a 15 mA drive current. The Si chip is also connected to the second transistor of the Darlington pair. This connection provides a current sink that improves the delay time associated with switch turn-off. The figure also shows the inclusion of a SiC "fly-back" diode.[9] This component is required for switches that large reactive loads (ex. high power electricl motors).

In addition to presenting design details for both the SiC Darlington pair and the silicon chip, the following sections, present initial test results from a CMOS test chip that was fabricated using a 1.5 µm CMOS process available through the MOSIS service.[10]

3.1. Silicon Carbide Device

This section describes the material layer structure, transistor design and expected performance for the NPN bipolar junction transistors that make up the Darlington pair. Figure 3 shows an epitaxial layer structure for the NPN SiC transistor grown in the emitter up configuration. The layer thicknesses and doping levels have been optimized with the use of a 2d device simulation package.

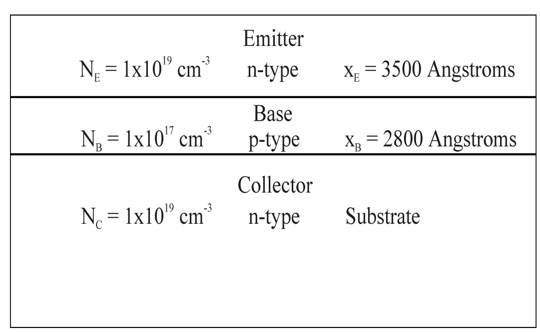
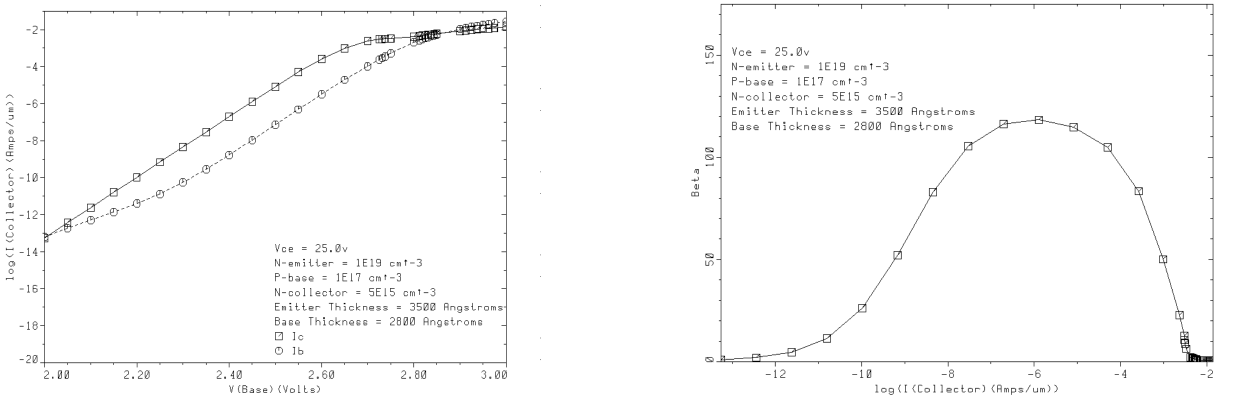


Figure 3 Silicon Carbide layer structure used to fabricate Darlington Pair.

Figure 4a) shows simulated I-V characteristics for the base-emitter and the base-collector junctions. Figure 4b) show the gain vs. collector current characteristics for the simulated device. The simulation shows that the proposed layer structure is expected to have a maximum current gain of 118 A/A.



a) b)

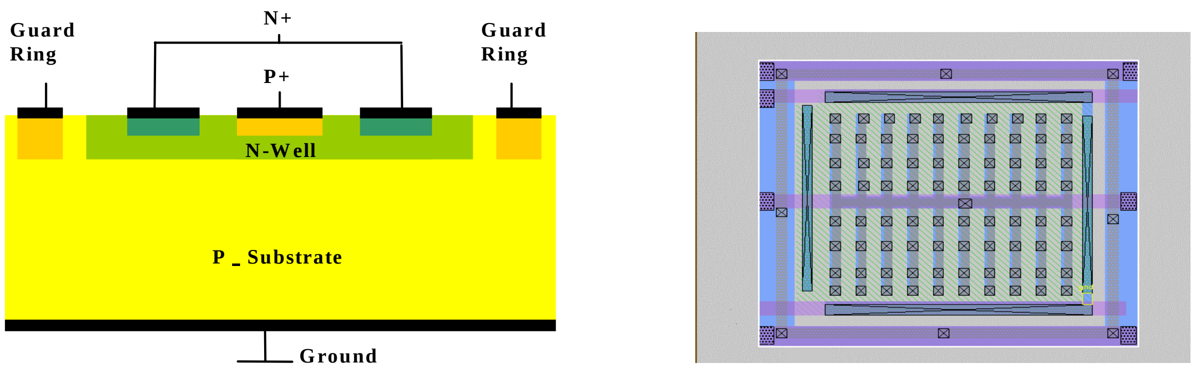
Figure 4 Simulated electrical characteristics for the layer structure shown in figure 1 with V_{CE} = 25V and the V_{BE} stepped from 2V to 3V. a) Base and collector currents as a function of base bias. b) Gain vs. Collector current.

Further devices fabricated from this layer structure could exhibit current gains greater than 100 for collector current densities ranging from ~10 nA/μm^2 to ~100 mA/μm^2. These simulations were done assuming that the collector to emitter voltage is 25 volts. While this is approximately a factor of 5 smaller than the expected bias potential, these results are expected to hold so long as the base layer thickness is increased to compensate for the expansion of the base-collector space charge region associated with increasing the collector to emitter bias potential.

3.2. CMOS Compatible Photodiode Structures

Figure 5 shows a the cross section and VLSI layout for a PN junction photodiode that can be implemented using a P+ diffusion into the N-well of a conventional CMOS fabrication process. The photodiode is typically implemented with a multiple P+ fingers biased in parallel. A guard ring is included around the N-well to isolate the device from adjacent devices. The structure is biased by applying a negative voltage to P+ contact. With a positive potential applied to the N-well contact and the P-substrate connected to ground, both of the PN junctions in the structure are reverse biased. Thus it is possible to use either junction as a photodiode. In general the N-well to P-Substrate diode can be considered to have significantly higher sensitivity but typically has turn-off times greater than 1 μs. The motor controller that this work is targeting requires switching speeds of ~ 1 μs. Thus, the P+ to N-well diode has been used as a photodetector.

Figure 6 shows the detector current vs. optical power characteristics for the P+ to N-well diode when illuminated with a near infrared light source (λ = 853 nm). The measured responsivity is 0.09 A/W. This is significantly below the theoretical maximum of ~0.3 A/W that is achievable for silicon photodiodes operating in the near infrared.



a) b)

Figure 5 Cross section (a) and layout view (b) for a Silicon PN junction photodetector that is compatible with standard CMOS fabrication processes.

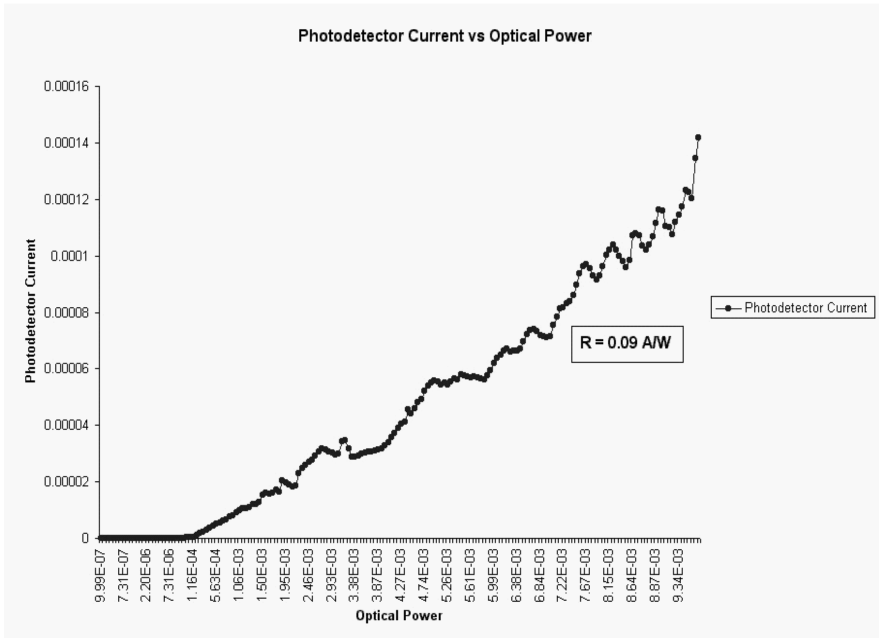


Figure 6 Detector current vs. optical power for the P+/N-well photodiode.

3.3. Photoreceiver Circuit

As shown in Figure 7 the photodetector described above is incorporated into a photo receiver circuit that consists of a photodiode and a two-stage amplification circuit. The optical input is approximately 1mW. With the detector responsivity of 0.09 A/W, the photodiode produces a current of 90 μA. The photocurrent flows through an active load (transistor M1). The resulting voltage at Node A is amplified by two push-pull amplifiers M2/M3 and M5/M6. The dimensions for all transistors were selected to provide an output voltage swing from Ground to Vdd for an input optical power swing from 0-1mW. SPICE was used to verify the sizing of all transistors.

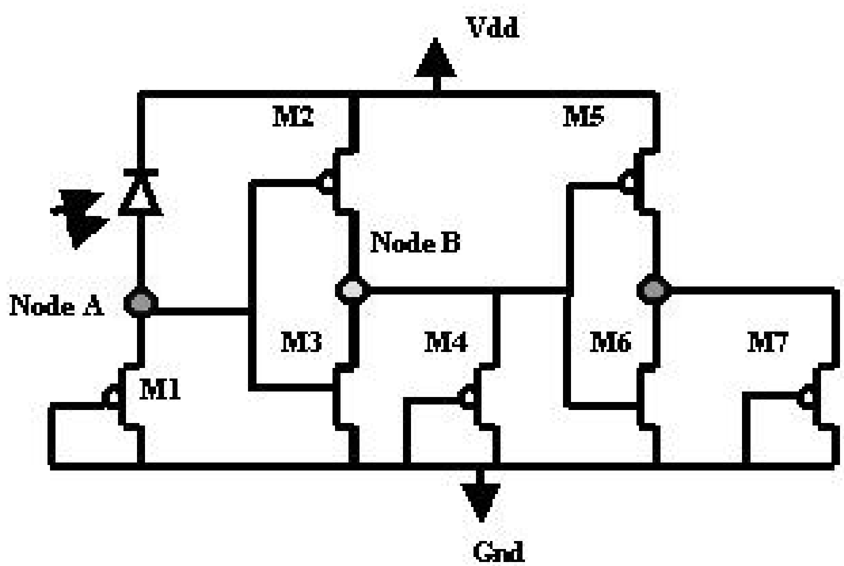


Figure 7 Photorecevier circuit consisting of a photodiode, an active load (M1) and two push-pull amplifier stages.

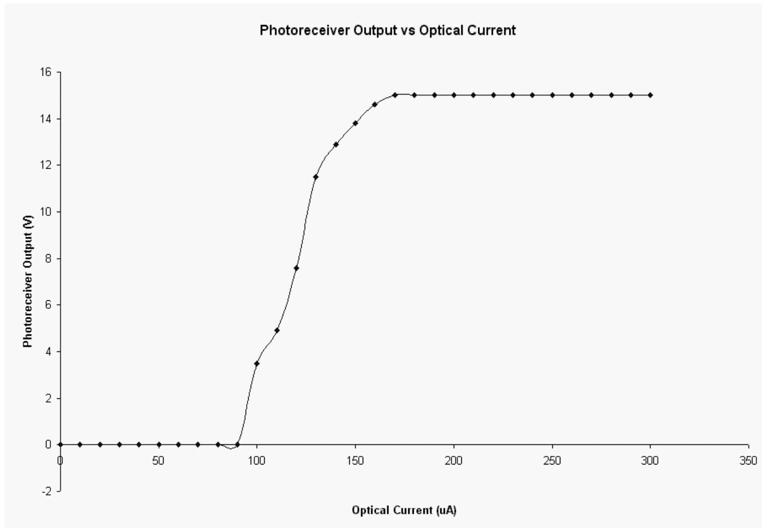


Figure 8 Output voltage vs. photodetector current for the photoreceiver circuit.

Figure 8 shows measured output voltage vs. photodetector current characteristics. For this measurement, Node A was driven with a current source at a level similar to that of the photogenerated optical current coming from the photodiode. As shown in figure 8, optically generated currents less than 90 μA produce negligible output voltage. For currents greater than 90 μA (corresponding to an optical input power of ~1 mW) the photoreceiver output voltage increases linearly. A 1.9 mW optical signal illuminating the photodetector leads to a 170 μA optically generated current that produces a fully on output voltage from the photoreceiver. For currents greater than 170 μA, the photoreceiver output voltage is fixed at the power supply voltage.

3.4. Current Drive Circuit

For the silicon carbide device to act as switch it must produce a stable 150 A of drive current. Thus, it is necessary to drive the SiC Darlington pair with a stable current drive source. Figure 9 shows the CMOS circuit that is used to provide a stable 15 mA drive current in the ON state and a constant sink current in the OFF state. As suggested in figure 9, the circuit has three major components: a dual port current source, a pair of Bipolar Junction Transistors, and a current sink

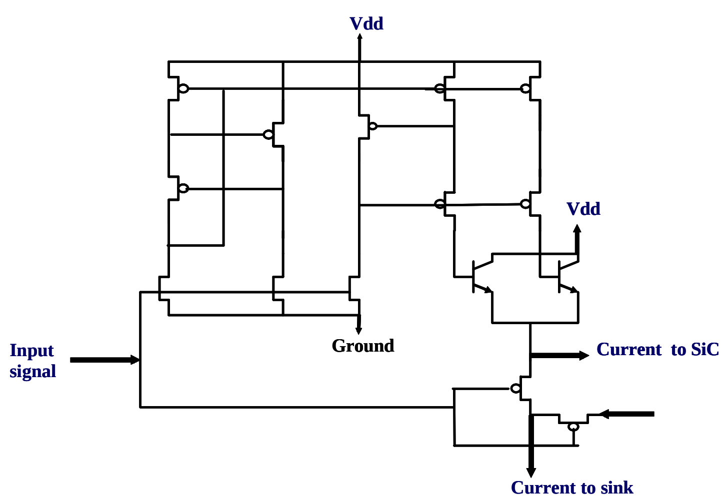


Figure 9 Drive current circuit diagram comprised of a dual port cascode current source and a pair of BJT. Also shown are two PMOS transistors that control connection of the SiC device to the discharge current source.

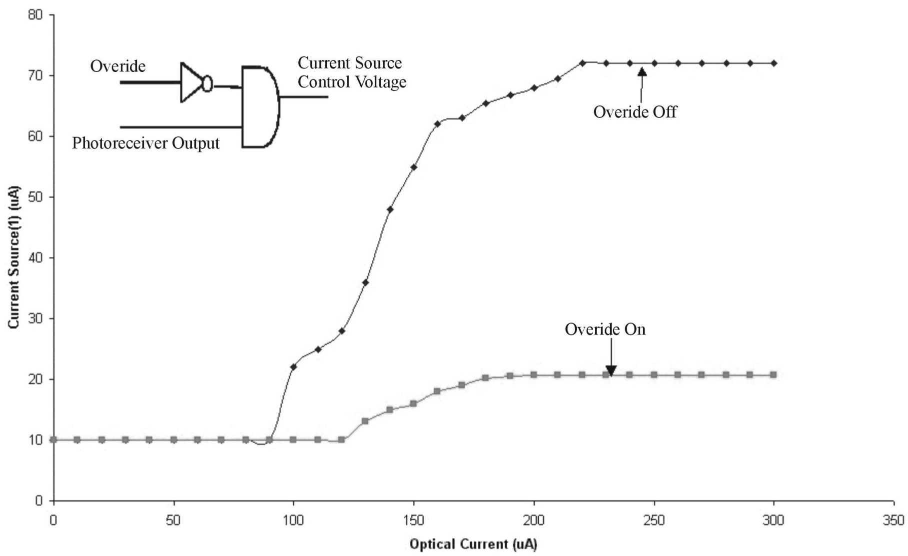


Figure 10 Current source output current vs. photodetector current for both states of the overide signal.

for discharging both transistors in the Darlington Pair. The dual port current source must provide stable operation over a wide range of output potentials. A voltage regulated cascode current mirror is used to increase the output resistance of the current source. As a result, as long as the sourcing transistors operate in the saturation region, a constant current flows from each of the current source output ports. The magnitude of the source currents is controlled by an input control signal. The current source is designed such that each port will source 70 µA when the input control signal is 15 Volts. When the control signal is 0Volts, the output from both ports of the current source drops to 0 µA.

As the circuit inset for figure 10 indicates, the current source control voltage is generated by combining the receiver output voltage with an override signal. When the over ride signal is ON, the current source control voltage goes to the ground potential. When the override signal is OFF, the current source control voltage tracks with the photoreceiver output voltage. Figure 10 shows that the output current from one of the current source ports for both states of the override signal.

The current generated by each output port of the current source is driven into the base of a bipolar junction transistor (BJT) that is biased in a common emitter configuration. The BJTs are used for their high current capability which leads to in increase in speed when driving large capacitive loads and a decrease in problems associated with noise. A BiCmos process is used to fabricate the device. A vertical NPN BJT is implemented which uses the n-well as a collector , a p-base diffusion for the base and the n+ implant for the emitter. From the drive circuit shown in figure 9, a 70uA current flows into the base of each BJT producing ~7.5mA flowing out of each BJT emitter. The total current from the two BJT is 15 mA which is sufficient drive current to produce 150A from the SiC Darlington pair.

Finally, as shown in figure 9, two PMOS transistors are used to control the Darlington pair discharge path. By connecting the bases of both Darlington transistors to a current sink, it is possible to insure that the switch can be turned OFF quickly. With out a mechanism for removing charge from the bases of the Darlington transistors, the frequency characteristics of the switch would slowed by long tails in the turn-off phase. To prevent the discharge path from effecting the ON characteristics of the switch the PMOS transistors are controlled by the same voltage that is used to control the dual port current source. Thus, when the current source is ON, the PMOS transistors are turned off and the source current is driven through the BJT's to the SiC Darlington. When the current source is OFF, the PMOS transistors are turned ON and the current sink pulls charge out of the bases of the Darlington transistors.

3.5. Short Circuit Failure Detection Circuit

Failure of the SiC power transistors results in a short circuit condition that can be detrimental to both the silicon chip and the motor controller that uses these optically controlled high power switches to control a large electric motor. Since the controller uses six switched to control drive current for a three phase motor, it is possible to use the collector-emitter voltage across a working SiC Darlington pair to detect the failure of the other switches. When the SiC Collector-Emitter voltage exceeds 12 volts for more than a few microseconds, a failure condition is recognized. A comparator circuit is used to monitor the system for short circuit failures. One input of the comparator is the collector-emitter voltage from the SiC device. The other input to the comparator is tied to a 12 volt reference voltage that is generated from the 15 volt power supply using a voltage divider. The output of the comparator controls a timing circuit that determines if the possible short circuit condition has persisted over more than a few microseconds. (Note: the Collector-Emitter voltage will also exceed 12 volts for a brief time when ever the switch is turned ON). Once a failure condition has been detected, the override circuit shown in the inset to figure 10 can be used to override the normal operation of the smart chip and isolate that failed circuit from the other switching devices and/or the motor controller.

4. CURRENT STATUS OF SWITCH DEMONSTRATION

Although we have demonstrated that several of the key circuit components are functioning as designed, we have yet to demonstrate operation of the complete switch. Presently, two components of the switch circuit are not working correctly. First, due to an error in the CMOS layout, proper operation of the Silicon BJTs prevents the smart Si chip from driving 15 mA into the SiC Darlington pair. Second, problems with ohmic contacts on the SiC have prevented the demonstration of working SiC transistors. We are currently working to overcome these problems and expect to demonstrate a fully functional optically controlled high power switch in the near future.

5. CONCLUSION

In this paper, we have described the design, characterization and evaluation of a hybrid chip design that is suitable for use as an optically activated high power switch. The proposed device is well suited for application in Fly-by-Light avionic systems where optical control signals are used to drive the electric motors that actuate the flight surfaces of a modern aircraft. The hybrid device uses a SiC Darlington pair to provide a 150 A drive current. A smart silicon chip that includes a photoreceiver, drive current circuitry, and diagnostic circuits necessary for detecting short circuit failures has been fabricated using the AMI 1.5 micron MOSIS process. Initial test results have shown that many of the critical circuit elements are working. Demonstration of a 15mA drive current from the CMOS chip full operation of the SiC Darlington pair have yet to be completed. Reporting on the fully function optically controlled high power switch is expected once the problems with these components has been overcome

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