Custom Integrated Circuits Using A Dielectrically Isolated Process Exhibit Radiation Tolerance

Donald Anderson
Wireless Microsystems LLC

David Cox
Research Associate Professor
University of New Mexico

Steve McClure
Hughes Space And Communications

Abstract-**Most contemporary and historic bipolar integrated circuits are fabricated with junction isolated processes. The reverse-biased PN junction which is intended to isolate circuit elements can exhibit leakage currents after even moderate exposure to radiation. This leakage current can degrade circuit performance or cause failure. Similarly, many analog and mixed signal integrated circuits depend on PNP transistors as current mirrors, active loads, drivers or pass elements (in positive regulators). In a junction isolated process, most of these PNP devices are constructed using lateral geometries; also vulnerable to leakage and beta degradation due to radiation exposure. With dielectric isolation there is no isolation junction to contribute leakage and both NPN and PNP transistors are vertical structures with beta degradation very low compared to junction isolated (JI) processes, making them suitable for applications to several hundred Krads. This paper will explore the design of a low power adjustable positive regulator as an example, using a dielectrically isolated process, to evaluate behavior and performance before and after exposure to radiation.**

1 Introduction

Semiconductor processing, like most engineering endeavors , has compromises associated with accomplishing the desired results. An early industry objective was to be able to fabricate more than one component on a common substrate; the integrated circuit. This objective was accomplished by creating isolation between components with a reverse biased PN junction (JI-junction isolation). If the region between components, the substrate, was of a material that could be reverse biased relative to the desired components, almost no current would flow between devices and the circuit would function, to a reasonable extent, as if each element of the circuit was separate and independent. The isolation was never perfect, but good enough to permit integration of multiple transistors and resistors to create circuits.

If it works, don’t fix it. This approach of reverse junction isolation has been the predominant method for most of the history of the semiconductor industry. Driven by cost and scaling pressures, refinements have been made to this basic approach which are more than adequate for most applications. But, that does not make JI the only or best method for all applications.

In applications where the circuit is likely to be exposed to high or sustained levels of radiation, junction isolation has several failings [1]. Many effects come into play, including leakage currents, beta degradation (bipolar transistors) and threshold shifts (MOS transistors). It is not the intent of this paper to explore the physics of these phenomenon. But, for the satellite industry, it is important to embrace radiation as an issue which must be dealt with. There are alternatives to junction isolation.

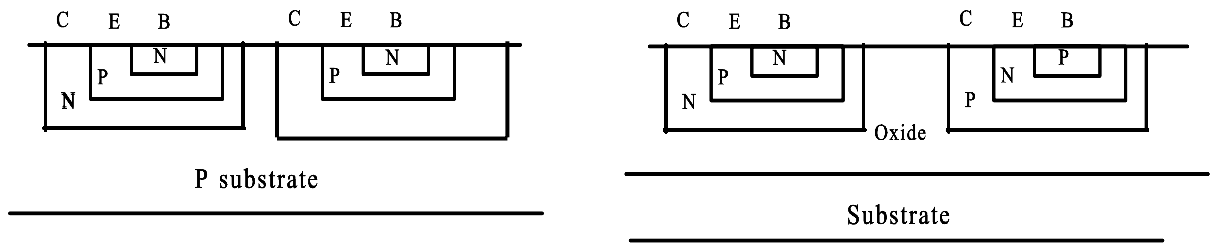
The MOS technologies have used silicon-on-insulator (SOI, SOS) and various processing techniques to deal with radiation. This paper addresses bipolar integrated circuits. They are not the dominant technology any more, but they remain important. There are certain applications which are better served by bipolar. But, bipolar can be very intolerant of radiation, especially where both NPN and PNP geometries are required. Most bipolar technologies favor NPN transistors. NPNs dominate most designs with PNPs created using lateral junctions. A vertical PNP is possible, provided the collector can be the substrate. But, consider the positive voltage regulator, where a PNP makes the best “pass element” to regulate current and voltage at a load. All three terminals must be available for such an application. A lateral PNP will be vulnerable to substrate leakage and beta degradation. But, there is an option.

Dielectrically isolated processes allow the creation of NPN and PNP transistors with substantially complimentary characteristics, insulated from each other by a wall of glass. This technology is not new, but it is not necessarily well known because it is not “cheap”, nor does it lend itself to very high component density. Having dispensed with the “down-side”, it is important to understand the benefits and potential of circuits designed in a DI process for radiation environments.

2 Dielectrically Isolated Process

The DI process used for the circuit described in this paper starts with an ordinary wafer. Regions of “N” and “P” material are implanted. The area around these implanted areas are etched and an oxide is grown such that it flows into the etched areas. A very thick silicon is grown on top of the oxide. The wafer is flipped, and what was the “ordinary wafer” is ground down to the point that only the regions of “N” and “P” material remain as islands in a sea of oxide. These islands are the tubs in which the transistors are created. A simplified comparison of JI vs DI is shown in figure 1.

To accomplish this “sea of oxide” takes added processing steps. And, the spacing between components is generally larger than the spacing with JI. So, the cost is greater. That is not desirable in a cost constrained commercial environment. But, when the objective is a satellite that requires minimum shielding and operates with longevity in the harsh environment of space, the benefits of DI can potentially make it the most cost effective solution.



JI process with NPN transistors

DI process with NPN and PNP transistors

Figure 1: Simplified cross-section of a JI vs. DI process.

3 Design Example-A Radiation Tolerant Positive Voltage Regulator

To demonstrate the relative merits of DI, a circuit was designed, simulated and fabricated. A positive voltage regulator was chosen for this purpose to help evaluate several attributes of the DI process. The introduction and process comments have emphasized leakage currents. The actual design focused more on beta degradation and Vbe shifts with radiation. The reason for this is simple; the DI process exhibits negligible leakage current, so this circuit attribute has minimal impact on the design.

Eight (8) commercially available positive adjustable regulators were evaluated at Hughes Space and Communications to determine their relative tolerance to radiation. These regulators, intended for applications from 100mA to 1.5A, included device types MIC29372, LT1528 and ADP3303. All of these devices failed primarily due to loss of pass transistor gain, with degraded regulation accuracy and low phase margin as radiation dose increased. The pass transistor gain was of most concern, as this limits the maximum output current. The worst case condition was with no bias or low load current and low dose rate. Failure range for worst case conditions was anywhere from 5 Krads to 30 Krads, depending on device. Most device types were able to survive to somewhat higher radiation levels with high dose rates at high output currents. The objective of this paper is the design of a positive adjustable regulator using the DI process, which can maintain output to greater than 100 Krads exposure while maintaining good accuracy.

The design example, a low power voltage regulator, consists of three principle subsystems; a bandgap reference, an op-amp for voltage comparison and a pass element to maintain load voltage at some value referred to the bandgap voltage. The circuit schematic is shown below in figure 2.

In the upper left hand corner of the schematic is a start-up circuit. When bias is applied to the terminal labeled “IN”, this circuit gets current flowing in the current mirrors across the top bus (Q40 on the left-top to Q53 on the right-top). It effectively “shuts-off” once the bandgap biases up. The bandgap reference consists of transistors Q5-Q12 compared to transistor Q13. Bandgap phenomenon is well described in many texts on linear IC design; Gray and Meyer [2] as an example. A temperature stable reference at the bandgap voltage is created by the ratio of the Vbe of Q5-Q12 vs the Vbe across Q13 [3 – 6]. This voltage will nominally be 1.15 Volts based on the models for the DI process used for this simulation.

An op-amp compares the output voltage of the regulator to the bandgap reference. The op-amp can be seen in the middle-right of the schematic. The comparison occurs at the input of

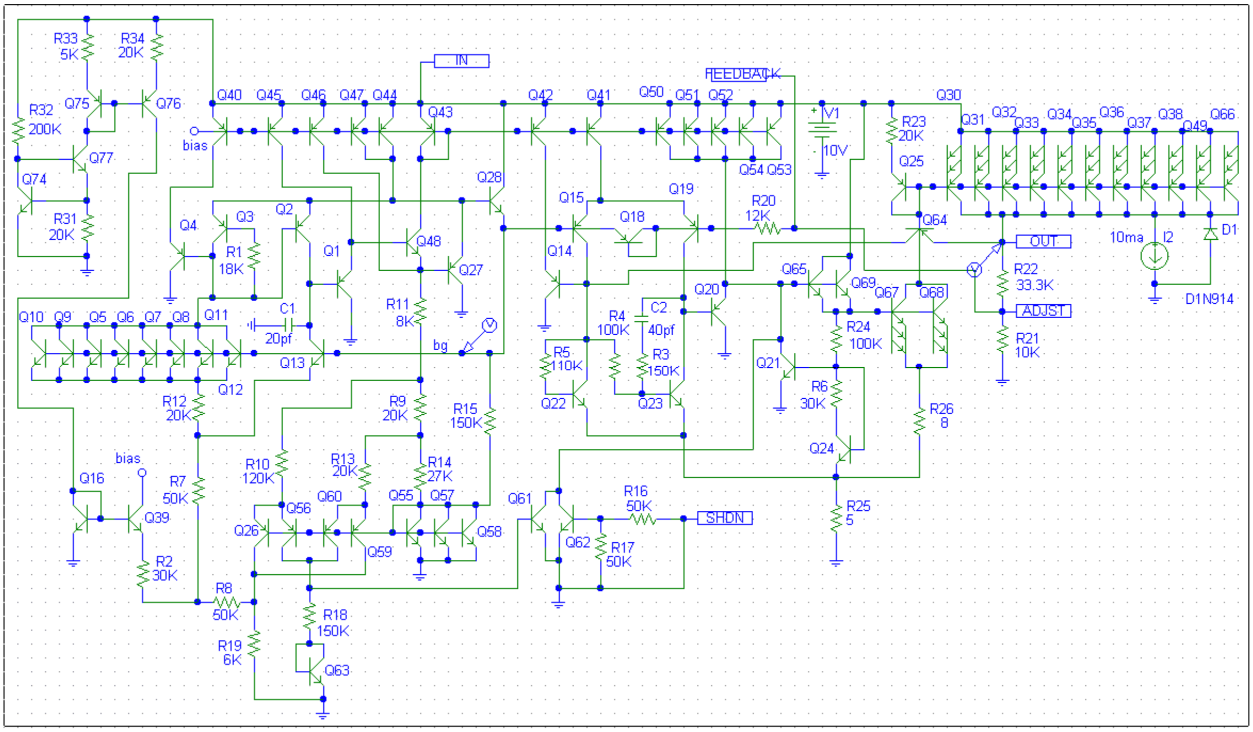


Figure 2. Voltage regulator circuit schematic.

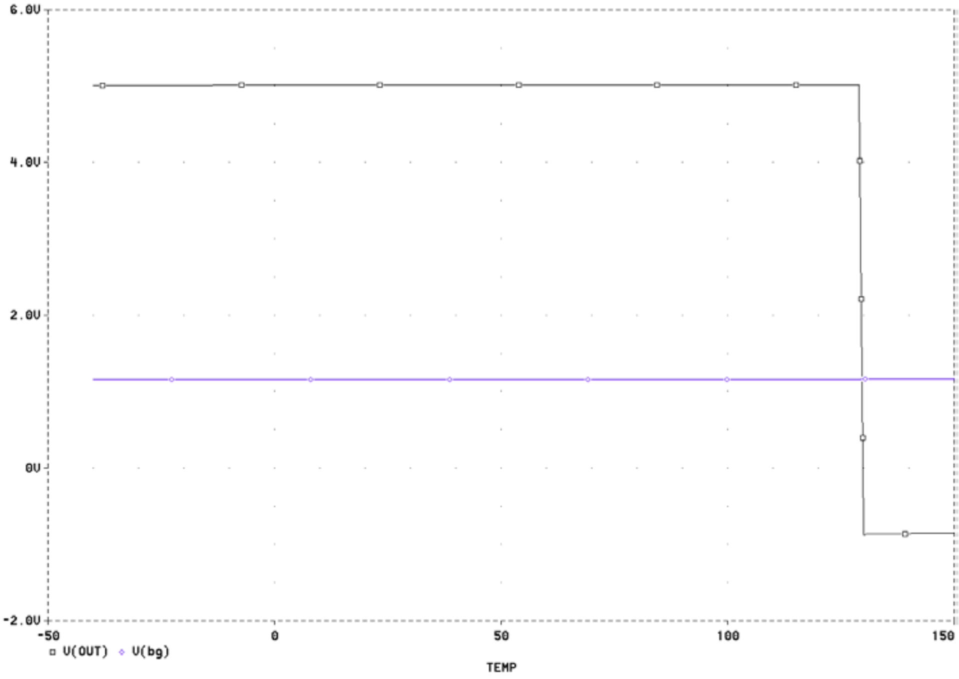


Figure 3. Regulated Output Voltage From -40°C to +150°C.

the op-amp, with Q15 connected to the bandgap voltage and Q19 connected to the feedback point from the output. Both of these transistors are PNPs, requiring independent access to the collector, base and emitter. A JI vertical PNP could not be used here. In a JI process these transistors would have to be lateral devices, subject to both the leakage and beta degradation.

The output pass transistor of this regulator is found in the upper-right of the schematic. It consists of 33 parallel-connected PNP devices. In a fully optimized design, the pass transistor would be specially designed for the voltage and current required. For purposes of this paper an array was developed to permit adjustment once initial performance could be empirically tested. Standard transistors were connected in parallel to reduce risk (by using known geometries). This will ultimately limit the output current, relative to an optimized design, to about 750 mA. This is a practical amount of current for local regulation in a real application. In a conventional regulator flying in space, this pass element is usually "the first to go" as beta decreases and output current can no longer be maintained. The output voltage vs. temperature is as shown in Figure 3.

Internal resistors for this circuit were fabricated with polysilicon doped for about 500 Ω/sq. Capacitors were of sandwich construction with thin oxide between N+ and metal. Most resistors were either non-critical or dependent on ratios rather than absolute value to minimize effects of changes with radiation. External resistors are used between the OUPTUT, FEEDBACK and GROUND pins to set the output voltage relative to the bandgap voltage.

The accuracy of this regulator will depend on the bandgap reference accuracy [7 – 11] and the ability of the internal op-amp to maintain "stiff" feedback. Based on simulations with an input voltage of 10 Volts and load current of up to 1 Amp, with the external feedback resistors setting the output voltage at 5 Volts, the output voltage vs. temperature is shown in Figure 3.

4 Radiation Effects on Components

Radiation effects on the process were evaluated at Hughes Space and Communications' Radiation Laboratory. Due to time constraints to meet the schedule for this conference, high dose rates were used to determine relative component degradation effects. Low dose rate testing will be performed on the actual circuit once fabrication is completed. As indicated above, the leakage effects were minimal. The principal impact of radiation was on beta. An example of beta degradation with DI compared to a typical JI process (considered for this design until the results were analyzed) is shown for reference in Table 1.

Transistor Type	**Pre**	**60Krads**	**100Krads**	**200Krads**
npn(DI)	100%	92%	87%	78%
pnp(DI)	100%	63%	50%	34%
npn(JI)	100%	55%	30%	19%
pnp(JI)	100%	5%	-	-

Table 1: Beta degradation with radiation-DI vs JI

Table 2 shows how Vbe changed with radiation. This parameter will have direct impact on the absolute accuracy of the regulator after exposure to radiation. The data is taken from the worst-case sample and the percentage changes are shown. Base-emitter current was 100ua.

Pre	60Krads	100Krads	200Krads
.7475	.7435	.7395	.7375
(100%)	(99.46%)	(98.93%)	(98.66%)

Table 2: Vbe change with radiation (volts).

5 Simulated Performance

Simulations were performed to determine how the regulator would perform after various exposure to radiation. Input voltage was set at 10 Volts with the output set, using an external resistor voltage divider, at 5.01 Volts. The focus of the initial simulation was on load regulation, with load current of 1 Amp. Table 3 indicates how the DI regulator will behave with exposure to 60 Krads, 100 Krads and 200 Krads as beta is degraded. Beta was changed directly in the Spice model for the simulation runs according to Table 1. The thermally-sensitive current cut-off point occurred around 130°C and did not seem to be affected by the radiation.

Pre(volts)	60K	100K	200K
5.01	5.01	5.008	5.004

Table 3: DI regulation with radiation to 200 Krads.

Absolute accuracy of the regulator will depend on how stable the bandgap is with radiation. Table 4 indicates how much change will occur in the output voltage as the Vbe of the transistors in the DI bandgap were changed due to radiation in the range of 60 Krads to 200 Krads. The Spice reverse saturation current was modified to achieve the desired Vbe percentage change. Beta changes with radiation were also accounted for in the simulations.

Pre(volts)	60K	100K	200K
5.01	4.995	4.975	4.975

Table 4: Regulation with Vbe Changes Due to Radiation.

6 Conclusions

Junction isolated bipolar integrated circuits which depend on the performance of lateral PNP transistors are vulnerable to radiation. Hughes Space and Communications has confirmed this with the evaluation of commercially available adjustable voltage regulators. They are typically only able to sustain 30 Krads of radiation exposure before the lateral PNP transistors fail to support output current and cause instability due to phase shift. Dielectrically isolated bipolar processes represent a superior alternative for regulators or any circuit which depends on the performance of PNP transistors..

A low power adjustable voltage regulator has been designed which utilizes a DI process to improve on the performance of JI under radiation. Based on measured properties [12] of components from the DI process and simulation of the regulator, operation to greater than 200 Krads is possible. In addition to good load regulation after exposure to radiation, the bandgap reference in the DI process will provide regulation accuracy on the order of 1% even after 200 Krad exposure. The simulator used was PSPICE [13] from Orcad Corporation. The subject regulator has been tooled and is in fabrication. Results of the test circuit will be reported.

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