RADIATION-HARDENED MICRO-ELECTRONICS FOR NUCLEAR INSTRUMENTATION

Background

The successful development and deployment of future fission and thermonuclear fusion reactors depends to a large extent on the advances of different enabling technologies. Not only the materials need to be custom engineered but also the instrumentation, the electronics and the communication equipment need to support operation in this harsh environment, with expected radiation levels during maintenance up to several MGy. Indeed, there are yet no commercially available electronic devices available off-the-shelf which demonstrated a satisfying operation at these extremely high radiation levels.

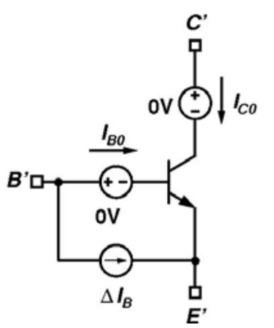
Objectives

The main goal of this task is to identify commercially available radiation tolerant technologies, and to design dedicated and integrated electronic circuits, using radiation hardening techniques, both at the topological and architectural level. Within a stepwise approach, we first design circuits with discrete components and look for an equivalent integrated technology. This will enable us to develop innovative instrumentation and communication tools for the next generation of nuclear reactors, where both radiation hardening and miniaturization play a dominant role.

Principal results

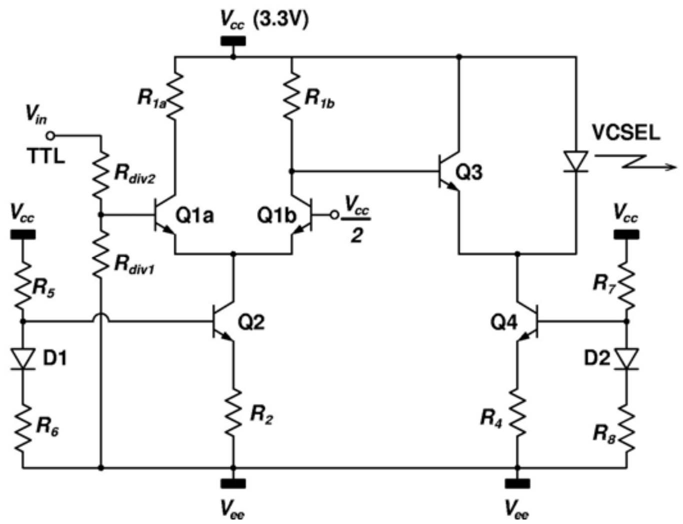
Our first R&D efforts resulted in an adapted SPICE model for a specific discrete Si bipolar junction transistor (BJT). This model describes the DC behaviour, including a time-dependent radiation induced degradation, hence enabling the design of a laser diode driver which still operates at 10 MHz up to 10 MGy. Unfortunately these Si BJT's became unavailable. A viable alternative was sought in a bandgap-engineered SiGe Heterojunction Bipolar Transistor (HBT), for which we also developed a compact physics-based SPICE model extension describing the behaviour of the transistor when exposed to γ-radiation up to MGy dose levels.

The radiation-aware SPICE model for the SiGe HBT is based on the presumably dominant physical degradation mechanism, obtained from early experiments which showed that the reduction in current gain stems from an increase in Shockley-Read-Hall recombination in the base-emitter space charge region. This is due to the production of Generation-Recombination centres caused by radiation induced lattice defects. As a consequence, the base current of the transistor is increased. Our presumption is supported by the fact that the excess base current during irradiation has been shown to be inversely proportional to the square root of the collector current. This insight was used to reduce the model complexity to only five coefficients. The resulting model has a very broad range of validity covering the entire design-space of interest.



$$\Delta I_B(D) = \left(c_1 + c_2.e^{c_3.D} + c_4.e^{c_5.D}\right).\frac{I_{B0}}{\sqrt{I_{C0}}}$$

Radiation-aware sub circuit for a SiGe npn transistor.

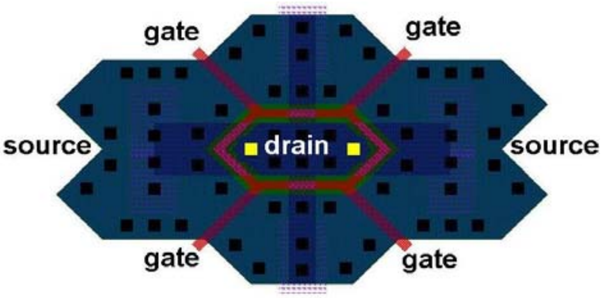


Schematic diagram of the proposed SiGe HBT-based circuit-hardened digital VCSEL driver.

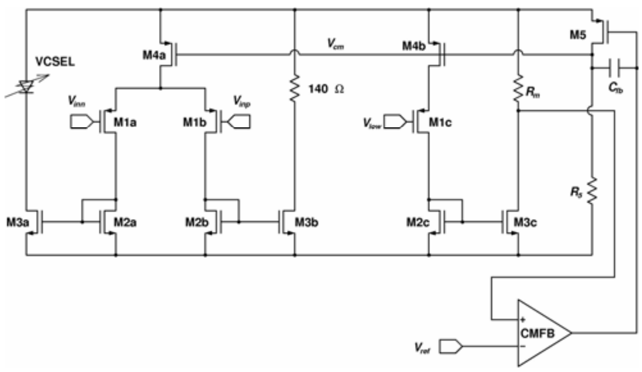
A digital vertical-cavity surface-emitting laser (VCSEL) diode driver was then realized using this discrete SiGe HBT. Simulations were used to design the circuit and predict its behaviour under radiation. Note that by adding a diode (D1) in the divider chain the temperature dependence is largely reduced. Simulations predicted a current increase of only 2 % when temperature is raised from 20 °C to 90 °C; i.e. a reduction by a factor 10 compared to pure resistive biasing.

The driver tolerates high levels of gamma radiation, up to a total dose of 12 MGy, and features less than 2 % drift in the forward current delivered to the laser diode. The output duty cycle measured in-situ showed about 1 % decrease at 200 kHz. Off-line measurements were also performed to describe and explain the circuit operation at elevated temperatures. Before irradiation, the output current of the driver (12 mA at 25 °C) increases with less than 1 % up to a temperature of 85 °C, which fits well with our simulations. After irradiation, the temperature tests revealed a recovery effect which is linked to the recovery of the individual transistors' current gain. Finally, measurements at an operation frequency of 10 MHz have demonstrated that the driver still meets its performance requirements up to 10 MGy.

As a step towards further integration, we have also developed a TTL compatible fully integrated 0.7 µm CMOS VCSEL driver for application in radiation environments. The design of the circuit tackles the damaging ionizing radiation effects both at circuit and layout level. The circuit can operate at least up to a frequency of 155 Mbps and is hence suited for the SONET OC-3 standard. The severe degradation of the output VCSEL current owing to radiation induced shifts in the transistors' threshold voltage is prevented by using a novel replica based feedback circuit. On the layout level a dedicated component library was built for increased radiation tolerance.



Layout of a hexagonal enclosed NMOS transistor.



Schematic of a circuit hardened VCSEL driver, using a replica-based feedback.

Low dose rate experiments up to a total dose of 3.7 kGy (370 krad) have shown that the 90 % decrease in VCSEL current without the feedback loop is limited to only 2 % when the feedback is included. A second experiment at a dose rate of 21 kGy/hr up to a total dose of 12 MGy has shown that the VCSEL current only drops by 10 % after a TID of 3.5 MGy (350 Mrad).

Future developments

Now that we have identified different radiation tolerant technologies, we are committed to the hardware design, construction and functional testing of a radiation-hard preamplifier, for its use with low-output sensors (e.g. strain-gauge based pressure sensors) in the remote handling equipment of the future ITER reactor.

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Main reference

P. Leroux, M. Van Uffelen, F. Berghmans, E. Simoen, C. Claeys, "A Compact, Broad-range, Physical SPICE Model Extension for the g-radiation Induced b-degradation in a Discrete SiGe HBT", submitted for publication in a IEEE Trans. Nucl Sci. issue.