Radiation Hardened Electronics for Critical Systems

Protecting the functionality of integrated control circuitry in high-energy environments

Since the advent of atomic weapons in the 1940s and of orbiting satellites a decade later, electronics designers have had to face the issue of how to sustain operation in the presence of damaging radiation to delicate, progressively miniaturized electrical components. The nomenclature for this operational resistance to high-energy (or "ionizing") radiation—such as the gamma radiation in space—is "radiation hard" (abbreviated "rad-hard"), an indication that electronics are radiation-damage resistant and can continue to operate properly even in a high-intensity radiation environment.

Damaging Operational Environments

Application-specific integrated circuits (ASICS) are electrical components designed to function in specific electronic systems, and they are ubiquitous in both military and civilian control systems (fig. 1). If such control systems operate in high-energy environments, or if they may at some point be subject to such conditions, the only way to ensure functionality is by rad-hardening. For example, satellites in orbit inevitably accumulate a large dose of gamma radiation, neutrons, and charged particles from the sun over their operating lifetime. Nuclear weapons both generate such high-energy conditions and are potentially subjected to them. A nuclear explosion can send a pulse of radiation (in the form of gamma rays and neutrons) large distances from the explosion site, thus affecting the function of any ASICs in proximal control systems. In addition, during their operation, such weapons would very likely be subjected to defensive actions, including high-radiation measures by adversaries attempting to disable their control systems, which must therefore be rad-hardened. Military sensors in the field can likewise be subjected to radiation during adversarial attempts to corrupt their functionality.

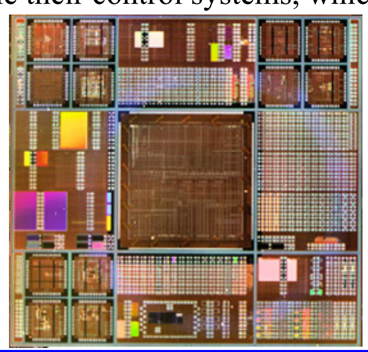

Figure 1. Sandia rad hard ASIC chip.

The common feature of these high-energy environments is the ionization of atoms and molecules in the component material of the ASICs, both directly changing electronic structure and creating holes (or sinks) that attract electrons from other molecular components. Wherever it impacts the atoms of an absorbing material within an ASIC, a high-energy neutron, for example, can wreak havoc, successively ionizing (knocking electrons from) atoms, leaving a trail or collection of electrons that can flow through the material to switch on a transistor, open an electronic gate, change a resistor's value, add an unexpected "bit" to a computer calculation, ablate a memory, or short out a capacitor. In general, passive electronic components can change their electronic values or short-out via current flows initiated by the electrons freed through such ionizations, while active components such as transistors can switch from off to on or vice-versa. ASICs

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composed of millions of transistors can easily cease functioning entirely or are highly likely to miscommunicate critical control or sensor information.

Sandia's Long-term Commitment to Rad-hardening

Since the mid-1960s, Sandia researchers have worked to reduce the sensitivity of control systems, communications systems, firing sets, and sensors, to such damaging radiation impacts, thus preserving control integrity under these extreme conditions. While LDRD projects have only impacted rad-hardening since the LDRD program's inception in 1991, radiation hardening of electronics was actively pursued at Sandia, largely in secret, during the 1960s and 1970s. The DoD/US military was the Laboratories' primary customer and worked closely with Sandia and several commercial vendors to find new materials and to understand radiation-damage physics. Originally, the simplest approach to rad hardening was to pre-irradiate electronics to attempt to saturate the damage level, that is to "pre-damage" the material while retaining functionality. Such treatment reduced circuit gains, but it also was reasonably effective at limiting further damage. Since most commercial electronics manufacturers were selling to the military, they worked closely with Sandia to rad-harden their products. However, by the mid-1970s, as very large scale integrated circuitry was entering the landscape, the consumer electronics market exploded. Consequently, by the early 1980s, commercial vendors had turned away from the military market, which was now only a minor portion of the economic landscape.

Today, only Sandia and Honeywell remain contributors to the radiation hardened electronics manufacturing market, developing new solutions to reduce component size to the nanoscale and increase capability in high-dose and pulsed-radiation environments. Sandia supplies rad-hardened components to customers, such as NNSA, NASA, the Navy, and the Air Force for both aerospace and weapons applications. Sandia purchases commercial electronics engineered to customer specifications or, using electrical-circuit simulations, designs and fabricates rad-hard ASICs for its various customers.

Material Science Innovations and Applications

To thwart radiation damage, Sandia LDRDs have employed fundamental materials science initiatives to study different materials such as silicon-on-oxide, gallium arsenide, germanium, and chalcogenides, materials that restrict the flow of electrons freed by gamma radiation and neutrons, and that therefore limit the damage when compared to silicon—the standard material for microelectronic circuitry. Some materials, like the chalcogenides (sulfur, selenium, and tellurium exemplify chalcogen elements) use physical phase changes rather than charge storage for memory retention. Other solutions include the use of use optical rather than electronic interconnects to maintain intra-circuit communications.

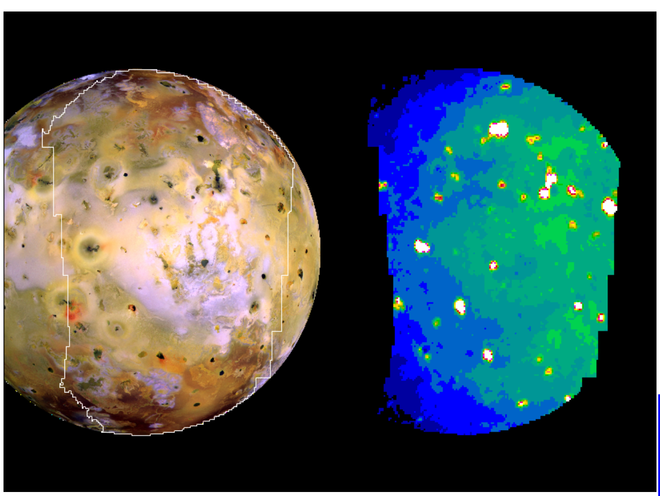

Figure 2. Colorized images of Jupiter's moon, Io, taken by the spacecraft, Galileo.

Along these lines, a significant Sandia contribution to the space program is exemplified by the NASA spacecraft, Galileo, which carried out an investigation of the planet Jupiter and its moons during the 1990s (fig. 2). Sandia designed, fabricated, and tested the radiation-hardened integrated circuits on the spacecraft, which returned enormous quantities of data from highly challenging radiation-filled environments such as that of the Jovian moon, Io, to which Galileo passed in rather close proximity. The Mars Rover (fig. 3) exemplifies another spacecraft requiring rad-hard ASICs to enable functionality in the high-radiation environment of space.

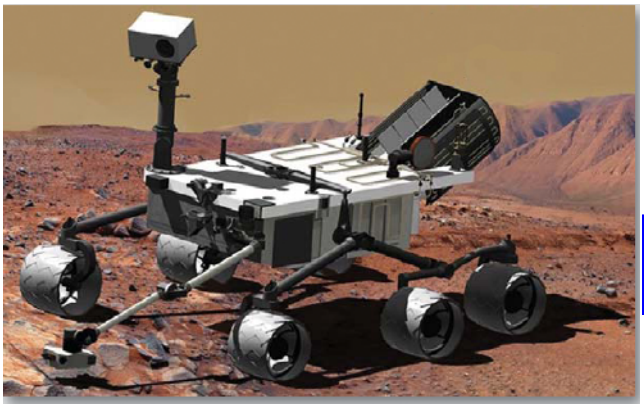

Figure 3. Artist's conception of the Mars Rover.

The launch of the entirely Sandia engineered Multispectral Thermal Imager (MTI) (fig.4) in 2000 is illustrative of the Laboratories' and LDRD's contribution to US and international space initiatives with rad-hardened electronics. A space package that was commissioned to fly for three years, primarily as a radiometric and thermal detector of nuclear proliferation, MTI has flown for about a dozen years. In addition to monitoring the atmosphere for evidence of activities involving nuclear materials, it has returned data regarding valuable geophysical and environmental monitoring and assessment, in areas such as volcanoes, glaciers, climate change, and studies of the moon.

C-RAM and Rad-hardened Insulators

LDRD projects have continued to contribute new concepts for rad-hardened computer memories, sensors, interconnects, and capacitors, primarily, although not exclusively applied to weapons and avionics. A 1996 project addressed processing techniques for silicon-on-insulator memories that were based on the presence of defects to reduce the transport of radiation-induced charges through the material. Such memories have subsequently become commercial off-the-shelf products. During 2003-2004, a new concept was examined to produce highly radiation-hardened memories using chalcogenides, for example, mixtures of germanium, antimony, and tellurium. These devices based memory upon phase changes in crystal structure that immensely increased

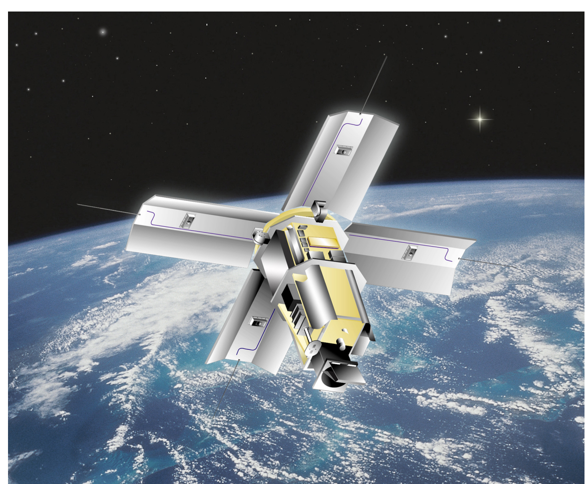

Figure 4. Artist's conception of the Multispectral Thermal Imager in orbit above earth.

local electrical resistance, to create a computational "bit" of stored memory. The polycrystalline state (low resistance) provided the "zero" and the amorphous state (~1000-times greater resistance) provided the "one." These devices were coprocessed with the Air Force Research Laboratory, and today this C-RAM (chalcogenide random access memory) is another off-the-shelf product, an outcome of Sandia LDRD-funded research.

Another LDRD project addressed the radiation sensitivity of capacitors, a ubiquitous charge-storage component in ASICs. Such charge stored in capacitors can be easily and inappropriately released (discharged) by gamma rays, neutrons or other energetic charged particles, so the project developed a new insulator that would permit high stand-off voltages while having extremely limited electrical current flow when exposed to radiation sources. Beginning with Mylar, a commonly used insulator, but one that was not radiation resistant at high voltages, project staff doped Mylar with trinitro-fluorenone (TNF)—which had been previously used to produce coatings on auto windows for sunroofs—thereby dramatically increasing its rad-hardness. And when TNF became unavailable after its reclassification as an explosive, the team had to resort to clever chemical engineering. By devising novel synthetic techniques, they still managed to dope Mylar and demonstrate significantly improved rad-hard capacitors fabricated in-house.

One major outcome of the LDRD investment in the science and technology of radiation hardening is the global recognition of its capabilities leadership. For example, in the late 1990s, the Intel Corporation chose Sandia to rad-harden its Pentium computer processor for space and defense applications, in simultaneous recognition of both national need and Sandia's unique capabilities. Recently, Sandia has collaborated with IBM, Boeing, and Honeywell in a DTRA program investigating rad-hard computing technologies for space applications.

Rad Hard LDRD projects have provided creative opportunities for LDRD researchers to directly contribute to the nuclear weapons and defense systems arenas, as well as to fundamental chemistry and chemical engineering research. These investigations seeking continual improvements in the areas of rad-hardening of integrated circuits represent advances in materials science that will undoubtedly continue to manifest positive outcomes in a variety of national security areas.