New Dimensions in Radiation Effects

B.D. Weaver
Electronics Science and Technology Division

Introduction: For satellites to be useful in space applications, they must survive the harsh radiation environment of Earth's van Allen belts. Onboard components are continuously bombarded by high-energy protons, electrons, ions, and cosmic rays, which degrade device performance and ultimately cause system failures. Thus in maximizing a satellite's operating lifetime, it is important to know how various devices will respond to radiation damage, and to incorporate radiation-tolerant components into the design.

Radiation Effects: When high-energy particles strike a device, they create structural defects that can alter device performance. The effect of defects on performance depends largely on the physics of device operation. Consider, for example, the case of conventional electronic devices—devices for which the physical dimensions are sufficiently larger than the carrier mean free path that carrier transport occurs by diffusion. Enough is known about how conventional electronic devices respond to induced disorder that their radiation tolerance can often be predicted by referring to existing data. Minority carrier devices, for instance, are generally quite sensitive to radiation damage because induced defects can trap charge carriers, serve as centers for recombination, and thereby affect the carrier concentration. In contrast, radiation-induced defects in majority carrier devices act mainly to scatter carriers in three dimensions (3D), and so have little effect on performance because transport is already diffusive and 3D. As a result, majority carrier devices are generally much less sensitive to radiation damage than minority carrier devices. If carrier transport is not conventional—for example, if electrons move ballistically or if transport occurs in fewer dimensions than three—then existing databases of radiation effects are not likely to exist. In this case, radiation tolerance must be determined directly by experimentation.

Reduced dimension has a particularly striking effect on radiation tolerance. Perhaps the best example is that of low- and high-temperature superconductors (LTSs and HTSs). In an isotropic LTS, paired carriers scatter elastically from radiation-induced defects but do not depair because all directions are effectively the same. In HTSs, paired carriers exist only in two-dimensional (2D) Cu-O planes. When they scatter from radiation-induced defects, the probability is high that they will be ejected from their planes and thus cease to contribute to the superconducting state. As a result, HTSs are about three orders of magnitude more sensitive to radiation damage than isotropic LTSs. In high electron mobility transistors (HEMTs), in which carriers move from source to drain via a 2D electron gas (2DEG), the dominant radiation effect arises from high-efficiency scattering of carriers out of the 2DEG. Similarly, in resonant tunneling diodes, the main radiation effect arises from high-efficiency scattering out of 2D quantum wells. As evidenced by the fact that a single defect in a carbon nanotube can mean the difference between a metallic and a semiconducting state, quasi-1D devices show evidence of being even more sensitive to disorder than 2D devices. Given the current emphasis on miniaturization and the trend of increasing disorder-sensitivity with decreasing dimensionality, the suitability of future devices for space application has been doubtful.

Until now.

Cellular Devices: Recent radiation damage experiments on conventional (3D) photodiodes, 2D multiquantum well (QW) photodiodes, and quasi-0D quantum dot (QD) photodiodes have shown, surprisingly, that QW devices can be 10-30 times more radiation-tolerant than bulk devices, and QD devices, can be 300-1000 times more tolerant. In these devices radiation tolerance actually increases as dimensionality is reduced. The reason, NRL researchers believe, is that QD (and to a lesser extent, QW) devices are composed of a large number of individual subdevices that act in concert to produce the overall response, much in the same way that cells in the as human pancreas collectively produce insulin. In this sense, each quantum dot can be likened to a *cell* and the congregation of cells can be called a *cellular device*.

Because charge carriers in QD cellular devices are confined to nearly 0D they cannot migrate to and interact with remote defects. As a result, the radiation-sensitivity of QD devices does not depend on the minority/majority carrier status or on the presence or absence of diffusive transport. Instead, it depends on whether a given cell has been hit by an incident particle, and if so, how much damage the particle has done. That is, in conventional and most nonconventional devices, performance is affected when mobile carriers encounter and interact with defects, but in cellular devices *the defects must come to the carriers*. This change in paradigm is thought to be the cause of the high radiation tolerance of QD devices.

To further understand this phenomenon, NRL scientists have altered a formalism from the 1940s for describing the survivability of irradiated living tissue into a theory of radiation effects for cellular devices in general. The new "cell theory" combines methods from probability and statistics to determine the fraction of damaged cells as a function of particle fluence, and uses displacement damage theory to describe the function of an impaired cell. The overall device response turns out to be a function of the particle fluence, the cross-sectional area presented by an average cell to an incident particle, and the effectiveness with which an average impact destroys a single cell's function. Remarkably, cell theory predicts that if all other parameters remain the same, decreasing the cell size always leads to an improvement in radiation tolerance.

This discovery could feasibly revolutionize the way radiation-resistent components are designed.

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