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Weatherford, Todd R.

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Historical Perspective on Radiation Effects in III–V Devices

Todd R. Weatherford, *Senior Member, IEEE,* and Wallace T. Anderson, Jr., *Member, IEEE*

***Abstract*—A historical review of radiation effects on III–V semiconductor devices is presented. The discussion ranges from examining early material and device studies to present-day understanding of III–V radiation effects. The purpose of this paper is to provide present researchers with a summary of discoveries and lessons learned from previous failures and successes.**

***Index Terms*—Compound semiconductor, gallium arsenide, radiation effects.**

I. Introduction

RADIATION effects in semiconductors are of concern for a broad range of device applications. Various applications and environments require knowledge of a wide range of radiation effects such as total-dose, dose-rate, soft errors, and displacement damage. Radiation effects research on compound semiconductors has been pursued since the 1960s in an effort to meet the needs of the nuclear power industry, national security, space systems, and the computer industry. These industries were fueled by a growing semiconductor industry. The choice of substrate materials initially started with elemental semiconductors such as Ge, Si, and Se and further spread when compound semiconductor substrates became available. In this paper, we mainly discuss those devices fabricated on Group III–V substrates. This paper focuses on the performance and reliability of these semiconductor devices when operated in radiation environments.

Previous authors have presented reviews on radiation effects in compound semiconductors. In 1973, Chaffin reviewed work from the late 1960s on displacement damage and ionization effects in GaAs [1]. Simons presented a review in 1983 of total dose, dose rate, and displacement damage effects [2]. In 1985 and 1989, Zuleeg presented reviews on GaAs radiation effects related to weapon and space applications on complementary junction field-effect transistor (JFET) devices [3], [4]. In 1988, Srour and McGarrity provided a review of GaAs radiation effects [5]. After 1990, other reviews discussed more recent findings [6], [7].

The following review provides: 1) a history of the studies of radiation effects in compound semiconductors; 2) the important milestones and discoveries; 3) information on how parameters were developed; and 4) how fundamental aspects of III–V device technology affected radiation hardness.

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T. R. Weatherford is with the Naval Postgraduate School, Monterey, CA 93943 USA (e-mail: trweathe@nps.navy.mil).

W. T. Anderson, Jr., is with the Naval Research Laboratory, Washington, DC 20375 USA (e-mail: wanderson@nrl.navy.mil).

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II. Historical Aspects

A. Early Compound Semiconductors and Devices

Brattain and Bardeen created the first bipolar germanium transistor in 1947 [8]. Welker presented the first discussion of compound semiconductors in 1952 [9]. Additionally in 1952, Shockley developed the first silicon field effect transistor (FET) [10]. Common compound semiconductors in 1959 ranged from various oxides (ZnO) to ZnSe and SiC, but GaAs was not important at that time [11]. The first GaAs bipolar transistor superior in performance to a silicon device appeared in 1961[12]. Mead developed the first GaAs FET in 1966, a metal-semiconductor field effect transistor (MESFET) [13]. Van Tuyl reported on GaAs FET integrated circuits in 1974 [14]. The first InP digital circuit was reported in 1981 [15]. The performance of these new compound semiconductor technologies led to uses where performance expectations were higher than for silicon or germanium devices. A review of the GaAs and InP industry has been presented in several places [16]–[19].

Radiation effects are separated into two areas: ionization and displacement damage effects. Ionization effects include total-dose, dose-rate, and single-event effects. Displacement damage effects are produced by nonionizing energy loss, which induces damage to the crystal by particle strikes, fast neutrons, thermal neutrons, protons, electrons, and ions.

The electronic device applications where these individual and combined radiation effects can influence components include:

- radiation detectors—all radiation sources;
- nuclear power controls—neutron, gammas;
- strategic weapons systems—fast neutrons, ionizing dose-rate, total ionizing dose;
- space systems—total ionizing dose, single-event effects, proton/electron displacements;
- natural terrestrial environments—single-event effects;
- IC packaging—single event effects.

As researchers investigated devices and components for these various applications, many papers appeared that presented experimental data, theoretical analyses, and failure rate predictions on radiation effects. Normally, III–V devices were compared to earlier silicon technology. Later, the newer compound semiconductor devices (i.e., InP, SiC, GaN) were compared to GaAs and Si. As transistor modeling software became available, researchers performed simulations of radiation effects on circuits and devices. Much of the latter work rests on parameter

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values obtained from the early studies of ionization and displacement damage effects. We must be cognizant of how our earlier colleagues obtained such parameters (i.e., ionization energies, rad conversions between materials, damage factors). Radiation effects studies on future semiconductor materials will require knowledge of these earlier procedures and techniques.

B. Early Radiation Studies: 1950s and 1960s

When TRANSACTIONS ON NUCLEAR SCIENCE was first published in September 1954 (as TRANSACTIONS OF THE IRE Vol. NS-1, no. 1) there were a total of three papers; these papers were concerned with nuclear reactor control and an electron accelerator. As stated in the editorial for that issue, it was hoped that the TRANSACTIONS published by the Professional Group on Nuclear Science would "be of real value to group members and a credit to the Institute." From that period to June 1959, the papers were concerned mainly with the nuclear power industry and nuclear research.

The scope of the IEEE TRANSACTIONS ON NUCLEAR SCIENCE was expanded in 1959 with a solid-state issue (NS-6, no. 2, June 1959) that included the first radiation effects paper on an electronic device, actually optoelectronic devices in the form of Si solar cells [20]. It was not until 1961 that the first paper was published [21] on radiation effects on a compound semiconductor device. This paper by Wright–Patterson AFB workers reported on the degradation of a GaAs unipolar transistor fabricated at RCA [22] according to a design proposed by Shockley [10]. It was found that the drain current degraded by 35% following 1-MeV electron irradiation to a fluence of 5×10^{17} cm^{-2}.

Following these papers, the first Nuclear Radiation Effects Conference (which later became Nuclear and Space Radiation Effects Conference, or NSREC) was held in Toronto, ON, Canada during June 1963; conference papers were published in Section I of the November 1963 issue of the IEEE TRANSACTIONS ON NUCLEAR SCIENCE (TNS). That issue also included invited papers on "Radiation effects in diamond lattice semiconductors" [23] and "Mechanisms of transient radiation effects" [24], both of which proved to be fundamental topics for future investigations.

Contributed papers appearing in Section II of the TNS November 1963 issue under "Steady state radiation effects" included a significant paper [25] on permanent damage in semiconductor devices and also established that "dislocation damage equivalence for various forms and energies of radiation is desirable in order to allow reasonable predictions of semiconductor component vulnerability for various missions." In that paper, silicon bipolar transistors and pn diodes were irradiated with 10-MeV protons, nuclear reactor neutrons, 5-to 25-MeV electrons, Cobalt-60 gamma rays, and Bremsstrahlung radiation from stopping 5-MeV electrons.

Another important paper in that first TNS issue compared radiation damage in GaAs and Si solar cells [26]. From a study of degradation in efficiency of the devices following irradiation by 0.8-MeV electrons, 5.6-MeV electrons, and 18-MeV protons, it was concluded that GaAs solar cells were more radiation resistant than Si solar cells. This occurs because recombination centers created by radiation-induced displacement damage have a larger degrading effect on carrier lifetime in the Si solar cell since the pre-irradiation lifetime is much larger in Si than in GaAs.

TABLE I
IONIZED CHARGE PER UNIT LENGTH FOR A ION HAVING A LET OF 1 MeV-cm^2/mg

Target Semiconductor	eV / eh-pair	Density (gm/cm^3)	Ionized charge fC/um	Conversion factor to divide pC/um to obtain MeV-cm^2/mg
Si	3.6	2.32	10.4	97
GaAs	4.8	5.32	17.8	56
InP	4.5	4.81	17.1	58
$In_{0.47}Ga_{0.53}As$	2.9	5.49	30.3	33
SiC	8.7	3.21	5.9	169
GaN	10.3	6.11	9.5	105

From the late 1950s through the late 1960s, the research emphasis was on displacement effects in detectors and solar cells. By the end of the 1960s, the radiation effects community began concentrating on ionization studies (as opposed to displacement studies). Little was presented on ionization effects in GaAs during that period. By 1968, many researchers were investigating electron-hole pair creation energies in Si and Ge [27]. Klein [28] provided ionization energies verses bandgap energy for many semiconductors, including GaAs, GaP, SiC, CdS, PbO, CdTe, and others. The GaAs data in Klein's work was attributed to Wittry [29] and Pfister [30]. Wittry's value of 4.8 eV/e-h pair is commonly used for GaAs. Table I includes predictions of ionized charge per unit path length for ion tracks in various semiconductors derived from Klein's ionization energy relationship. Recently, spectral responsivity techniques have been used to measure a 4.6 eV ionization energy for GaAsP and confirm the 3.6 eV value for Si [31]. Even though a large bandgap leads to a large ionization energy for electron-hole pair creation, the density of the target material is critical in determining ionization per unit length. As shown in Table I [7], low-density and large-bandgap semiconductors should be preferred in ionization environments in order to minimize susceptibility to ionizing particles. Equivalent ions produce more charge per unit length in GaAs than Si. Ionization charge tracks in InP are comparable to GaAs. Note that future InGaAs devices should be even more susceptible to ionization effects.

C. Device Radiation Effects: 1970s and 1980s

Following the first NSREC conference, the period from 1970 to 1990 saw a great deal of radiation effects research as GaAs and related compound devices became more prevalent. The high electron mobility of GaAs was attractive for ultra-high-frequency applications. During the development of GaAs devices, rapid advances were occurring in Si MOSFET manufacturing techniques. The wide use of MOSFETs was observed in the dominance of papers in the TNS addressing silicon MOS devices radiation effects. The MOSFET's gate and field oxides for both MOSFETs and silicon bipolar devices were a susceptibility issue for total dose effects. Neither GaAs bipolar transistors nor GaAs MESFETs included any oxides, so these devices had minimal susceptibility to total dose effects.

The majority of 1970s publications on GaAs device radiation effects examined displacement effects that reduced transistor performance. These publications examined the degradation of lifetime and mobility by neutrons. McNichols studied the effects of fast neutrons on GaAs junction JFETs and compared his findings to measurements to Si JFETs [32]. It was found that for GaAs devices irradiated in the fluence range of 10^{14} to 10^{16} n/cm^2 and with initial carrier concentrations of 10^{16} to 10^{18}/cm^3, the hardness level was predicted to be nearly the same as for n-type Si JFETs, with Si p-type JFETs having a lower hardness level. The radiation hardness level was based on a 20% decrease from the initial carrier concentration. In another study of neutron effects on GaAs devices [33], Gunn diodes were irradiated with neutrons from a fast burst reactor at fluences up to 1×10^{14} n/cm^2. It was found that the hardness level for power failure increased with increasing initial carrier concentration. Hardness levels were determined to be 2×10^{13} n/cm^2 at 3.3×10^{14}/cm^3 and 1.12×10^{14} n/cm^2 at 1.5×10^{15}/cm^3. A similar study [34] of epitaxial Gunn diodes and Hall samples demonstrated that device degradation resulting from neutron irradiation was due to a combination of carrier removal, low-field mobility decrease, and trapping of conduction electrons.

To investigate light-emitting diodes in a space environment, a study [35] was made of the degradation of various types of commercially available light emitting diodes at electron fluences up to 10^{15} e/cm^2. It was found that SiC had the highest radiation tolerance, followed by GaAsP, GaP, diffused GaAs, and epitaxial GaAs.

Borrega [36] examined the high total-dose hardness of GaAs microwave devices. Although GaAs devices were found to have total dose radiation hardness levels for gamma rays, X-rays, electrons, and neutrons comparable to these Si devices that do not have a gate oxide, it was found that GaAs FETs [37], [38] and photodiodes [39] experience a transient response after exposure to pulsed X-rays or electrons. These transients may be long-term and persist for times in the order of seconds at room temperature [38], [40]. The change in drain current following flash X-ray exposure occurred in both ion-implanted and epitaxial devices and was most pronounced at low drain current under large negative gate bias near pinchoff. The recovery time after exposure was found to be many orders of magnitude longer than that expected from ordinary photocurrent generation and decay. It appeared that the long-term transient effect was primarily due to charge trapping and its subsequent thermal release in the GaAs substrate material [38], [40], causing a "backgating" effect. Assuming this to be the case, GaAs FETs were fabricated with a buried p-layer by implanting Be just beneath the active n-layer to better isolate the active channel. Compared to similar GaAs FETs fabricated on the same wafer without a buried p-layer, it was found [41] that pulsed radiation induced drain current transients were reduced by two orders of magnitude following 100 rad X-ray pulses. Device performance was also improved, with the transconductance increasing by a factor of two.

As GaAs devices became more prominent in the early 1980s, total dose results on Si and GaAs devices were being compared to each other. Identical sources of radiation are absorbed differently in different target materials. For comparison of Co^{60} gamma sources the conversion between rad(Si) and rad(GaAs) also depended on the spectrum of the gamma source. For GaAs absorbed dose, a "dirty" or nonmono-energetic spectrum Co^{60} source may provide 18% more dose than a "clean" mono-energetic spectrum. Table II includes data on Si, GaAs, and InP for converting Roentgens to rads [42]. Note that the calculations in Table II are for bulk material where no oxide interfaces exist. GaAs absorbs less gamma energy per gram than Si or InP. However, note the difference in densities in Table I. The low density of Si results in less absorbed energy per unit volume.

TABLE II
ROENTGEN TO RAD CONVERSION FACTORS

Material	Mono-Co^{60}	Clean Spectrum	Dirty Spectrum
Si	.869	.869	.874
GaAs	.781	.817	.923
InP	.892	.892	-

By the early 1980s the Defense Advanced Research Projects Agency (DARPA) initiated development of radiation hardened GaAs digital technology [43], [44]. Parallel to this program was the Department of Defense's (DoD's) Microwave and Millimeter wave Monolithic Integrated Circuits (MIMIC) program that developed GaAs microwave circuits [45]. This technology development was to support the Strategic Defense Initiative (SDI) [46]. SDI applications focused on strategic and space environments. Thus, total-dose, dose-rate, neutron, and recently discovered soft-error effects were to be investigated with emerging GaAs IC technology. The total-dose requirement for SDI was difficult to achieve with MOS devices. Since GaAs devices: 1) did not employ oxides (thus having inherent total-dose hardness); 2) possessed a larger bandgap over Si for apparent lower ionization generation; 3) had high-resistivity substrates for isolation; and 4) provided superior transport characteristics, GaAs electronics appeared to be ideally suited for the SDI initiative. Additionally during this period, higher performance heterostructure transistors were being developed in the laboratory, and by the end of the decade VLSI heterostructure AlGaAs/GaAs ICs were in production [47].

As digital ICs and MMICs were developed from discrete GaAs devices, radiation effects were found to be important in these GaAs ICs. The first IC latch-up due to dose-rate effects was reported [48] in 1982. Transient radiation (dose-rate) effects were studied in RF power discrete GaAs MESFETs [49] and MMICs [49], [50] and hardness levels were established. More accurate total-dose measurements were also reported for GaAs devices [51] and MMICs [52]. Neutron radiation effects were reported [53] for MMICs under RF power including combined pulsed X-ray and pulsed neutron irradiation to more accurately simulate a nuclear event [54]. Compound semiconductor devices, with respect to total-dose, dose-rate and neutron effects, were on track for the DARPA program.

Single event effects (SEE) were discovered just before the DARPA initiative [55]. In the study of SEE, it was found [56], [57] that permanent damage and even burnout occurs during heavy ion irradiation and a model was proposed [58] to explain the effects. In an extension of that model using the Monte Carlo method, it was possible to calculate the heating rate of each particle as it passed through the device at various locations [59]. Single event effects were found to be important in GaAs digital ICs with the first single event upsets (SEUs) reported [60], [61] in 1983 and 1984. Decoupling and circuit techniques previously applied to CMOS SRAMs offered limited success in GaAs JFET SRAMs [4], [62]. As more SRAMs became available for testing, the soft error rates showed higher sensitivities than bulk Si SRAMs [63]. Circuit analysis tools were used to study charge collection [64]. It was not until the following decade with device simulation that the SEE sensitivity in GaAs ICs was understood. Charge collection between silicon and GaAs devices was different due to both material and device structure parameters. Hopkins and Srour investigated charge collection on GaAs and Si diodes and suggested that funneling effects were minimal in GaAs [65]. That work was used to predict photocurrents for circuit simulations [63], [64].

The GaAs SEE issue was not solved and the DARPA initiative was essentially over by the end of the 1980s. The DARPA initiative funded several GaAs foundries and spawned many new firms in the wireless and optoelectronic industry. Many successes occurred. However, the digital GaAs industry was unable to compete with the lithography advances propelling the Si CMOS industry into personal computers. Wafer yield issues prevented continued funding for military digital GaAs IC applications [66]. The DoD was no longer a high volume customer compared to consumer applications. GaAs digital SRAMs could not compete with the Si SRAM market, nor could GaAs SRAMs provide SEU hardness approaching the CMOS/SOS SRAMs. GaAs analog applications, unlike digital, had moved to the commercial sector and showed profitability. Microwave and analog GaAs devices satisfied the neutron and ionizing dose-rate needs for ongoing military systems.

InP-based devices were also studied during this time period. In the 1980s, InP-based discrete devices were available for study. Transient radiation effects and total-dose studies were made on InP metal-insulator-semiconductor field effect transistors (MISFETs) and large-amplitude long-term transients, similar to those seen in unhardened GaAs FETs, were reported [67] following pulsed electron irradiation. These InP MISFETs were also found to have low total-dose hardness levels of only 5 krad as a result of charge trapped in the gate-insulating layer. Improved radiation hardness was achieved by elimination of the gate insulator using a JFET design. It was reported [68] that these InP JFETs exhibited only small transients when irradiated by pulsed electrons and had total-dose hardness levels of greater than 8×10^8 rads.

D. Radiation Effects in the 1990s

By the early 1990s, there were still programs utilizing digital GaAs ICs for space applications. The soft error issue was unresolved and required additional investigation [69]. SRAM soft error tests [70], [71] and charge collection experiments [72], [73], with the help of device simulation tools [74], determined that the SEE sensitivity was related to several items: 1) the uninsulated GaAs FET gate; 2) hole collection in the semi-insulating substrate that provided a mechanism to induce a bipolar transistor effect [73] or back-gate [74]; and 3) the low-doped substrate that provided long diffusion lengths, which increased collection volumes. Also, as noted in Table I, the ionization in GaAs per unit length is higher than that of silicon.

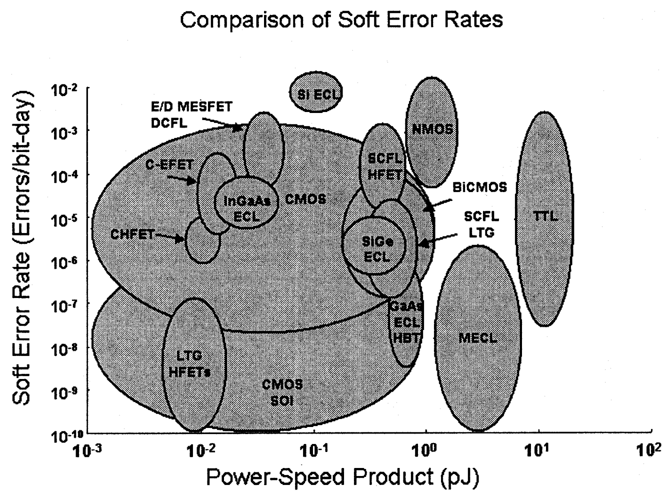

Fig. 1. Geosynchronous orbit soft error comparisons for various IC technologies.

Once the soft error issue was understood, techniques to increase substrate recombination via buffer layers mitigated the problem [75]–[77]. The use of low-temperature grown GaAs [78] in a buffer layer below the transistor was used. The buffer layer incorporated high defect densities of As antisites and Ga vacancies which increased electron trapping and recombination rates by three orders of magnitude. SEU-hardened GaAs ICs have been successfully implemented in satellites [79]. Other variations in the GaAs buffer layers provided improved recombination and reliability [80]. Fig. 1 shows a comparison of soft error rates for various IC technologies [7].

Single-event transient (SET) errors in GaAs were also important. During the 1990s, digital GaAs ICs were only being utilized for high-performance applications. Most GaAs ICs were utilized for data communications and not memory storage. In 1992, Schnierderwind [81] *et al.* presented experimental evidence of soft errors in GaAs MESFET combinational logic during dynamic switching conditions, not in static tests as normally performed on SRAMs. These soft errors in combinational logic were not unique to GaAs ICs, but were also experienced with other technologies [82], [83]. Techniques became available to measure signals on-chip at gigahertz clock rates. By late 1998, measurements of InP-based heterojunction bipolar transistor (HBT) ICs at 10 GHz showed susceptibility to multiple-bit errors in combinational configurations [84]. A substrate effect similar to that causing SEE sensitivity in GaAs FET devices was proposed [85].

A summary of milestones in III–V semiconductor radiation effects studies is shown in Table III.

TABLE III
TIMELINE OF RADIATION EFFECTS MILESTONES RELATED TO GaAs DEVICES

Year	Milestone
1961	Electron radiation effects on unipolars [21]
1970	Neutron irradiation of GaAs JFETs [32]
1978	Total dose measurements on GaAs MESFETs [36]
1979	First dose rate study of GaAs FETs [38]
	Dose rate studies on GaAs ICs [37]
1981	Dose rate effects on GaAs photodetectors [39]
1982	Dose rate latchup studies in GaAs ICs [48]
1983	First JFET SRAM SEU proton experiments [60]
	First JFET SRAM heavy ion SEU experiments [61]
1992	First experiments on dynamic SEU testing of GaAs SEU [81]

TABLE IV
RELATIVE COMPARISON OF GaAs TO Si DEVICES FOR SEVERAL RADIATION EFFECTS

Threat	Hardness relative to Silicon	Reasons why and comments
Total Ionizing Dose	Much Harder (to bulk Si) Less Harder (to Si SOI)	▪ Component devices do not trap charge ▪ No radiation-induced turn-on of parasitic MOS
Ionizing Dose Rate	Harder (to bulk Si) Softer (to Si SOI)	▪ Shorter minority carrier lifetime ▪ No radiation-induced turn-on of parasitic bipolars.
Displacement Fluence	Harder	▪ Higher doping levels ▪ Shorter minority carrier lifetime

III. FUNDAMENTAL OBSERVATIONS

A. Ionization Effects

1) Target Density: As evident from Table I, ionization-induced charge is related to both the target density and the electron-hole pair ionization energy. Wide bandgaps, high electron-hole pair ionization energies, and high resistivity were assumed to be sufficient to provide ionizing radiation hardness over silicon devices. The importance of target density is sometimes overlooked when comparing semiconductor technologies. Low-density wide-bandgap semiconductors such as GaN and SiC may be useful for consideration in ionizing radiation environments.

2) Substrate Collection: For dose-rate effects, the high-resistivity semi-insulating substrate was an improvement over a p-doped bulk Si substrate. However, the GaAs material included defects such as EL2, which was related to the As antisite. This defect trapped carriers over microseconds [86].

For SEE effects, the diffusion length in the semi-insulating GaAs substrate was on the order of microns to tens of microns, which is much longer than a diffusion length in a p-doped Si substrate. It was not until techniques were developed to reduce lifetimes in the GaAs substrate that the soft error issue was mitigated [74]. Doping the GaAs substrate would degrade isolation. The use of radiation damage to lower lifetime was not practical [87]. In many cases of radiation testing of GaAs SRAMs with heavy ions, the SEU hardness improved with fluence [88]. In the mid-1980s, superlattices were applied to the problem of ionization in the GaAs substrate [47]. Superlattices were not very successful for SEE, possibly due to long duration DX trapping centers in AlGaAs [89].

3) Noninsulating Gates: Ionization in the gate region of an FET creates photocurrents that directly connected to the gate node of the III–V FET. In MOSFET devices, the single-event photocurrent is related to the drain-to-body junction, whereas in most III–V FETs, the rectifying gate's depletion region is the source of the charge collection. Decoupling resistors in CMOS circuits protected gate nodes of MOSFETs from charge collection on drain nodes. Decoupling resistors in noninsulating gate devices prevents single-event-induced charge from being removed from the gate node. As seen in Fig. 1, as various gate junction technologies utilized higher Schottky barrier heights in the gate structure, the soft error rate decreased. However, after the substrate issue was solved with short-lifetime buffers, it was assumed that the substrate collection was the most critical issue in the SEE sensitivity of GaAs ICs.

B. Displacement Damage Effects

In the 1970s and 1980s, neutron weapon effects and later space trapped proton effects were examined. Displacement damage induces defects that degrade mobilities and introduce recombination centers. Displacement effects in bipolar devices increase base recombination. In homogenous bipolar devices, displacement damage is more critical than in heterojunction bipolar devices because base current is mainly due to hot carrier transport rather than diffusion. In FETs, the degradation of mobility or the creation of trapping centers is the limiting mechanism.

Another issue in studies of displacement damage effects in III–V devices is the ability to compare experimental results between various particle sources, specifically proton and neutron damage. Recently, Messenger *et al.* have provided a successful methodology to compare nonionizing energy-loss to experimental results in GaAs devices [90].

IV. CONCLUSION

Examination of the history of the III–V device field shows that radiation effects studies migrated from experimental studies of ionization and displacement effects in bulk materials during the 1960s and 1970s to experimental analyses of device effects in the 1980s. In some cases, GaAs IC designers borrowed MOS circuit hardening techniques without much success. Table IV provides an overall comparative summary of GaAs and Si device hardness to major radiation threats [91].

By the 1990s, further efforts to solve the SEE problem needed device simulation, new experimental techniques for dynamic circuits, and defect engineering techniques to arrive at a solution. For a solution to be attractive to commercial foundries, the hardening technique must not limit performance, must be timely for implementation, and must not increase costs. This scenario presents a difficult challenge for workers in the radiation-hardening field.

In early 2003, we observe that the GaAs foundries are switching over to InP-based devices. Many of the effects and mechanisms applicable to early compound semiconductors will also apply to new devices and materials. As these new devices continue to lower power-delay products, ionization effects (both space and terrestrial) may become more critical for many applications.

Another point related to the survivability of emerging technologies should be made. The changing geopolitical environment (SDI has ended) and economic environment (GaAs could not compete in the microprocessor or SRAM markets) essentially eliminated the digital GaAs market (one firm did survive). On the other hand, commercial analog GaAs devices became very profitable and manufacturers were not interested in offering devices for radiation-hardened applications. Whatever direction future semiconductor advances takes, the study of fundamental radiation effect mechanisms will continue to be based on the earlier contributions described herein.

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REFERENCES

[1] R. J. Chaffin, *Microwave Semiconductor Devices: Fundamentals and Radiation Effects*, 1st ed. New York: Wiley, 1973, pp. 129–142.
[2] M. Simons, "Radiation effects in GaAs integrated circuits: A comparison with silicon," in *1983 IEEE GaAs IC Symp. Dig.*, pp. 124–128.
[3] R. Zuleeg, "Radiation effects in GaAs ICs," in *VLSI Electronics: Microstructure Science*, N. G. Einspruch, Ed. New York: Academic, 1985, ch. 8.
[4] ——, "Radiation effects in GaAs FET devices," *Proc. IEEE*, vol. 77, pp. 389–407, Mar. 1989.
[5] J. R. Srour and J. M. McGarrity, "Radiation effects on microelectronics in space," *Proc. IEEE*, vol. 76, pp. 1443–1469, Nov. 1988.
[6] D. McMorrow *et al.*, "Single-event phenomena in GaAs devices and circuits," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 628–644, Feb. 1996.
[7] T. R. Weatherford, "Radiation effects in high speed III–V integrated circuits," *Int. J. High Speed Electronic Syst.*, vol. 13, no. 1, Mar. 2003.
[8] J. Bardeen and W. H. Brattain, "The transistor, a semiconductor triode," *Phys. Rev.*, vol. 74, p. 230, 1948.
[9] H. Welker, *Z. Naturforsch*, vol. 7a, p. 744, 1952.
[10] W. Shockley, "A unipolar field-effect transistor," *Proc. IRE*, vol. 40, pp. 1365–1377, Nov. 1952.
[11] J. N. Shive, *Semiconductor Devices*. Princeton, NJ: Van Nostrand, 1959, p. 11.
[12] M. E. Jones and E. C. Wurst, *IRE Conv. Rev.*, vol. 9, p. 26, 1961.
[13] C. A. Mead, "Schottky-barrier gate field effects transistors," *Proc. IEEE*, vol. 54, pp. 307–308, Feb. 1966.
[14] R. Van Tuyl and C. A. Liechti, "High speed integrated logic with GaAs MESFETs," in *Dig. Tech. Papers, ISSCC*, Feb. 1974, pp. 112–115.
[15] L. J. Messick, "A high-speed monolithic InP MISFET integrated logic inverter," *IEEE Trans. Electron. Devices*, vol. 28, pp. 218–221, 1981.
[16] P. Greiling, "The historial development of GaAs FET digital IC technology," in *IEEE Microwave Theory Tech.*, Sept. 1984, vol. 32, pp. 1144–1156.
[17] R. C. Eden, "The development of the first LSI GaAs integrated circuits and the path to the commercial market," *Proc. IEEE*, vol. 76, no. 7, pp. 756–777, July 1988.
[18] D. L. Lile, "The history and future of InP based electronics and optoelectronics," in *Int. Conf. Indium Phosphide and Related Materials Proc.*, May 11–15, 1998, pp. 6–9.
[19] M. Golio and B. Newgard, "The history and future of GaAs devices in commercial wireless products," in *Broadband Communications Internet Era Symp. Dig., 2001 IEEE Symp. Emerging Technologies*, 2001, pp. 63–69.
[20] F. A. Junga and G. M. Enslow, "Radiation effects in silicon solar cells," *IRE Trans. Nucl. Sci.*, vol. 6, pp. 49–52, June 1959.
[21] B. A. Kulp, J. P. Jones, and A. F. Vetter, "Electron radiation damage in unipolar transistor devices," *Proc. IRE*, vol. 49, pp. 1437–1438, Sept. 1961.
[22] C. C. Dacy and I. M. Ross, "Unipolar field effect transistor," *Proc. IRE*, vol. 41, pp. 970–979, Aug. 1953.
[23] J. H. Crawford, Jr., "Radiation effects in diamond lattice semiconductors," *IEEE Trans. Nucl. Sci.*, vol. 10, pp. 1–10, Oct. 1963.
[24] V. A. J. van Lint, "Mechanisms of transient radiation effects," *IEEE Trans. Nucl. Sci.*, vol. 10,, pp. 11–19, Oct. 1963.
[25] R. C. Brown, "Equivalence of radiation particles for permanent damage in semiconductor devices," *IEEE Trans. Nucl. Sci.*, vol. 10, pp. 54–59, Oct. 1963.
[26] J. J. Wysocki, "Radiation studies of GaAs and Si devices," *IEEE Trans. Nucl. Sci.*, vol. 10, pp. 60–65, Oct. 1963.
[27] G. Restelli and A. Rota, "Mean energy required for hole-electron pair creation and the Fano Factor," in *Semiconductor Detectors*, G. Bertolini and A. Coche, Eds: American Elsevier, 1968, p. 85.
[28] C. A. Klein, "Bandgap dependance and related features of radiation ionization energies in semiconductors," *J. Appl. Phys.*, vol. 39, no. 4, pp. 2029–2038, Mar. 1968.
[29] B. Wittry and D. F. Kyser, *J. Appl. Phys.*, vol. 36, p. 1387, 1965.
[30] H. Pfister, *Z. Naturforsch*, vol. 12a, p. 217, 1957.
[31] F. Scholze, H. Henneken, P. Kuschnerus, H. Rabus, M. Richter, and G. Ulm, "Determination of the electron-hole pair creation energy for semiconductors from the spectral responsivity of photodiodes," *Nucl. Instum. Methods In Phys. Res., Sec. A 439*, pp. 208–215, 2000.
[32] J. L. McNichols and W. S. Ginell, "Predicted effects of neutron irradiation on junction field effect transistors," *IEEE Trans. Nucl. Sci.*, vol. 17, pp. 52–54, Apr. 1970.
[33] G. H. Marcus and H. P. Bruemmer, "Radiation damage in GaAs Gunn diodes," *IEEE Trans. Nucl. Sci.*, vol. 17, pp. 230–232, Dec. 1970.
[34] N. Berg and H. Dropkin, "Neutron displacement effects in epitaxial Gunn diodes," *IEEE Trans. Nucl. Sci.*, vol. 17, pp. 233–238, Dec. 1970.
[35] A. G. Stanley, "Comparison of light emitting diodes in a space radiation environment," *IEEE Trans. Nucl. Sci.*, vol. 17, pp. 239–244, Dec. 1970.
[36] J. M. Borrego *et al.*, "Radiation effects on GaAs MESFET's," *IEEE Trans. Nucl. Sci.*, vol. 25, pp. 1436–1443, 1978.
[37] R. Zuleeg and J. K. Nothoff, "Transient response of GaAs IC's to ionizing radiation," *IEEE Trans. Nucl. Sci.*, vol. 26, pp. 4744–4749, Dec. 1979.
[38] M. Simons and E. E. King, "Long-term radiation transients in GaAs FET's," *IEEE Trans. Nucl. Sci.*, vol. 26, pp. 5080–5086, Dec. 1979.
[39] J. J. Wiczer, L. R. Dawson, and C. E. Barnes, "Transient effects of ionizing radiation in photodiodes," *IEEE Trans. Nucl. Sci.*, vol. 28, pp. 4397–4402, Dec. 1981.
[40] M. Simons, E. E. King, W. T. Anderson, Jr., and H. M. Day, "Transient radiation study of GaAs MESFET's implanted in Cr-doped and undoped substrates," *J. Appl. Phys.*, vol. 52, no. 11, pp. 6630–6636, Nov. 1981.
[41] W. T. Anderson, Jr., M. Simons, E. E. King, H. B. Dietrich, and R. J. Lambert, "Reduction of long-term transient radiation response in ion implanted GaAs FETs," *IEEE Trans. Nucl. Sci.*, vol. 29, pp. 1533–1538, Dec. 1982.
[42] C. Dozier, *Internal Naval Res. Lab. Memo. to M. Simons May 8*, 1984.
[43] S. A. Roosild, "Radiation-hardened GaAs integrated-circuit development," *The American Nuclear Soc.*, vol. 49, June 1985.
[44] ——, "The next step in GaAs digital electronics," *Microwave J.*, vol. 30, no. 12, Dec. 1987.
[45] A. Firstenberg and S. Roosild, "GaAs IC's for new defense systems offer speed and radiation hardness benefits," *Microwave J.*, vol. 28, no. 3, p. 145, 1985.
[46] S. Karp and S. Roosild, "DARPA, SDI and GaAs," *Computer*, vol. 19, p. 10, Oct. 1986.
[47] R. L. Remke *et al.*, "SEU measurements on HFET's and HFET SRAM's," *IEEE Trans. Nucl. Sci.*, vol. 36, pp. 2362–2366, Dec. 1989.

[48] R. Zuleeg *et al.*, "Latch-up in GaAs IC's during ionizing radiation exposure," in *1982 IEEE GaAs IC Symp. Dig.*, 1982, pp. 123–126.

[49] W. T. Anderson, Jr. and S. C. Binari, "Transient radiation effects at X-band in GaAs FET's and ICs," *IEEE Trans. Nucl. Sci.*, vol. 30, pp. 4205–4208, Dec. 1983.

[50] W. T. Anderson, M. Simons, A. Christou, and J. Beall, "GaAs MMIC technology radiation effects," *IEEE Trans. Nucl. Sci.*, vol. 32, pp. 4040–4045, Dec. 1985.

[51] A. Meulenburg, C. M. Dozier, W. T. Anderson, S. D. Mittleman, M. H. Zugich, and C. E. Caefer, "Dosimetry and total dose radiation testing of GaAs devices," *IEEE Trans. Nucl. Sci.*, vol. 34, pp. 1745–1750, Dec. 1987.

[52] A. Meulenburg, H.-L. A. Hung, K.E. Peterson, and W. T. Anderson, "Total dose and transient radiation effects on GaAs MMICs," *IEEE Trans. Electron. Devices*, vol. 35, pp. 2125–2132, Dec. 1988.

[53] W. T. Anderson, J. K. Callahan, and J. M. Beall, "Neutron radiation effects in GaAs MMIC's and FETs," *J. Radiation Effects, Res. Eng.*, vol. 6, no. 3, pp. 1–6, 1988.

[54] W. T. Anderson, R. C. Harrison, J. Gerdes, J. M. Beall, and J. A. Roussos, "Combined pulsed neutron and flash X-Ray radiation effects in GaAs MMICs," in *1988 IEEE GaAs IC Symp. Dig.*, pp. 53–56.

[55] T. C. May and M. H. Woods, "Alpha-particle-induced soft errors in dynamic memories," in *Proc. 1978 IEEE Int. Reliability Physics Symp.*.

[56] W. T. Anderson, Jr., A. B. Campbell, A. R. Knudson, A. Christou, and B. R. Wilkins, "Degradation in GaAs FET's resulting from alpha particle irradiation," *IEEE Trans. Nucl. Sci.*, vol. 31, pp. 1124–1127, Dec. 1984.

[57] W .T Anderson, A. R. Knudson, A. Meulenberg, H.-L. Hung, J. A. Roussos, and G. Kiriakidis, "Heavy ion total fluence effects in GaAs devices," *IEEE Trans. Nucl. Sci.*, vol. 37, no. 57a, pp. 2065–2070, Dec. 1990.

[58] F. A. Bout, W. T. Anderson, A. Christou, A. B. Campbell, and A. R. Knudson, "A mechanism of radiation-induced degradation in GaAs field effect transistors," *J. Appl. Phys.*, vol. 37, no. 2, pp. 581–590, 1985.

[59] C. Moglestue, F. A. Buot, and W. T. Anderson, "Monte Carlo particle simulation of radiation-induced heating in GaAs FETs," *Appl. Phys. Lett.*, vol. 59, no. 2, pp. 192–194, July 8, 1991.

[60] P. Shapiro, A. B. Campbell, J. C. Ritter, R. Zuleeg, and J. K. Notthoff, *IEEE Trans. Nucl. Sci.*, vol. 30, pp. 2065–2070, Dec. 1983.

[61] R. Zuleeg, J. K. Notthoff, and D. K. Nichols, "SEU of compleme6pntary GaAs static RAM's due to heavy ions," *IEEE Trans. Nucl. Sci.*, vol. 30, pp. 4533–4539, Dec. 1984.

[62] R. Zuleeg and J. K. Notthoff, "SEU hardening of GaAs E-JFET SRAMs," *J. Radiation Effects, Res. Eng.*, vol. 6, no. 2, p. 136, 1988.

[63] T. R. Weatherford, J. R. Hauser, and S. E. Diehl, "A study of single event in GaAs SRAM's," *IEEE Trans. Nucl. Sci.*, vol. 32, pp. 1470–1475, Dec. 1985.

[64] T. R. Weatherford, J. R. Hauser, and S. E. Diehl, "Comparisons of single event vulnerability of GaAs SRAMs," *IEEE Trans. Nucl. Sci.*, vol. 33, pp. 1121–1127, Dec. 1986.

[65] M. A. Hopkins and J. R. Srour, "Charge collection measurements on GaAs devices fabricated on semi-insulating substrates," *IEEE Trans. Nucl. Sci.*, vol. 31, p. 1116, Dec. 1984.

[66] S. Roosild, private communication, Feb. 2003.

[67] W. T. Anderson, Jr., G. E. Davis, J. S. Mateer, and D. L. Lile, "Ionizing radiation effects in InP MISFET's," *IEEE Trans. Nucl. Sci.*, vol. 31, pp. 1467–1470, Dec. 1984.

[68] W. T. Anderson and J. B. Boos, "Radiation effects in InP JFETs," *IEEE Trans. Nucl. Sci.*, vol. 32, pp. 4001–4004, Dec. 1985.

[69] T. R. Weatherford *et al.*, "Can digital GaAs be used in a space environment? A look at single event upset in GaAs," in *IEEE 1991 GaAs IC Symp., Tech. Dig.*, Monterey, CA, Oct. 20–23, 1991.

[70] B. W. Hughlock, G. S. LaRue, and A. H. Johnston, "Single-event upset in GaAs E/D MESFET logic," *IEEE Trans. Nucl. Sci.*, vol. 37, pp. 1894–1901, Dec. 1990.

[71] T. R. Weatherford *et al.*, "Proton and heavy ion upsets in GaAs MESFET devices," *IEEE Trans. Nucl. Sci.*, vol. 38, pp. 1450–1456, Dec. 1991.

[72] D. McMorrow, A. B. Campbell, A. R. Knudson, S. Buchner, and T. R. Weatherford, "Transient charge collection from ion tracks in semiconductors," *Nucl. Instrum. Methods Physics Res. Section B*, vol. 67, no. 1–4, p. 384, 1992.

[73] B. W. Hughlock, T. Williams, A. Johnston, and R. Plaag, "Ion induced charge collection in GaAs MESFET's and their effects on SEU vulnerability," *IEEE Trans. Nucl. Sci.*, vol. 38, Dec. 1991.

[74] T. R. Weatherford, D. McMorrow, W. R. Curtice, A. R. Knudson, and A. B. Campbell, "Single event induced charge transport modeling in GaAs MESFETs," *IEEE Trans. Nucl. Sci.*, vol. 40, pp. 1867–1871, Dec. 1993.

[75] P. W. Marshall *et al.*, "Heavy ion SEU immunity of a GaAs complementary HIGFET circuit fabricated on a low temperature grown buffer layer," *IEEE Trans. Nucl. Sci.*, vol. 42, pp. 1850–1855, Dec. 1995.

[76] T. R. Weatherford, D. McMorrow, W. R. Curtice, and A. B. Campbell, "Significant reduction in the soft error susceptibility of GaAs field-effect transistors with a low-temperature grown GaAs buffer layer," *Appl. Phys. Lett.*, vol. 67, no. 5, pp. 703–705, July 31, 1995.

[77] T. R. Weatherford, P. W. Marshall, C. J. Marshall, D. J. Fouts, B. Mathes, and M. LaMacchia, "Effects of low-temperature buffer-layer thickness and growth temperature on the SEE sensitivity of GaAs HIGFET circuits," *IEEE Trans. Nucl. Sci.*, vol. 47, pp. 2298–2305, Dec. 1997.

[78] F. W. Smith, A. R. Calawa, and C. L. Chen, "New MBE buffer used to eliminate backgating in GaAs MESFETs," *IEEE Electron. Devices Lett.*, vol. 9–2, pp. 77–80, 1988.

[79] M. LaMacchia *et al.*, "Radiation hardened complementary GaAs (CGaAs^{TM})," in *IEEE GaAs IC Symp. Tech. Dig.*, Oct. 1997.

[80] P. Specht, S. R. Zhao, R. C. Lutz, and E. R. Weber, "Growth and characterization of p-doped LT-GaAs," in *Symposium On Non-Stoichiometric III–V Compounds Proceedings*, vol. 6, Erlangen, Germany, Oct. 1998, p. 15.

[81] R. Schneiderwind, D. Krening, S. Buchner, K. Kang, and T. R. Weatherford, "Laser confirmation of SEU experiments in GaAs MESFET combinational logic for space applications," *IEEE Trans. Nucl. Sci.*, vol. 39, pp. 1665–1670, Dec. 1992.

[82] R. A. Reed *et al.*, "Single event upset cross sections at various data rates," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 2862–2867, Dec. 1996.

[83] C. J. Marshall, P. W. Marshall, M. A. Carts, R. Reed, S. Baier, and K. Label, "Characterization of transient error cross sections in high speed commercial fiber optic data links," in *Proc. IEEE 2001 Radiation Effects Data Workshop*, pp. 142–145.

[84] G. David *et al.*, "DC-to-mm-wave absolute potential measurements inside digital microwave IC's using a micromachined photoconductive sampling probe," in *IEEE MTT-S Int. Microwave Symp. Dig.*, New York, 1998, pp. 1333–1336.

[85] T. R. Weatherford and P. K. Schiefelbein, "SEE analysis of digital InP-Based HBT circuits at gigahertz frequencies," *IEEE Trans. Nucl. Sci.*, vol. 48, pp. 1980–1986, Dec. 2001.

[86] G. A. Baraff and M. A. Schluter, "Electronic aspects of the optical-absorption spectrum of the EL2 defect in GaAs," *Phys. Rev. B*, vol. 45, pp. 8300–8309, 1992.

[87] T. Matsukawa *et al.*, "Total dose dependence of soft-error hardness in 64 kbit SRAM's evaluated by single-ion microprobe technique," *IEEE Trans. Nucl. Sci.*, vol. 41, pp. 2071–2076, July 1994.

[88] T. R. Weatherford, "Single event upset in GaAs integrated circuits," Ph.D. dissertation, N.C. State Univ., Raleigh, NC, 1992.

[89] H. Mizuta, K. Yamaguchi, M. Yamane, T. Tanoue, and S. Takahashi, "Two-dimensional numerical simulation of Fermi-level pinning phenomena due to DX centers in AlGaAs/GaAs HEMTs," *IEEE Trans. Electron. Devices*, vol. 36, pp. 2307–2314, Oct. 1989.

[90] S. R. Messenger, R. J. Walters, E. A. Burke, G. P. Summers, and M. A. Xapsos, "NIEL and damage correlations for high-energy protons in gallium arsenide devices," *IEEE Trans. Nucl. Sci.*, vol. 48, pp. 2121–2126, Dec. 2001.

[91] B. L. Buchanan, "Radiation-hardened electronics," *Signal and Data Processing, Computers, and Electronics for Strategic Defense*, vol. II, Sept. 1992. Strategic Defense Initiative Technology Monograph.