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Physics of Failure and Radiation Effects in Emerging Electronic Materials and Devices in Space Applications

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14. ABSTRACT DoD systems require access to advanced electronic technologies, but it is difficult to qualify these technologies because of limited operational data and the complexity of the failure modes. Conventional reliability quantification methods are based on accelerated testing (with the acceleration typically provided by high temperature or bias), but these methods require understanding of the physical mechanisms responsible for device degradation to ensure that the same mechanisms are responsible for limiting the lifetime under both accelerated and normal operating conditions. Understanding the physics of failure in emerging technologies is thus a necessary condition for the deployment of these technologies in future DoD systems. This program conducted work to understand the physics of failure for emerging electronic technologies of particular significance to the DoD, with a focus on applications in a space environment. The specific technical areas we focused on are: (1) radiation effects in high speed devices and technologies and (2) reliability of GaN-based high electron mobility transistors (HEMTs).			
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Physics of Failure and Radiation Effects in Emerging Electronic Materials and Devices in Space Applications

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Accomplishments

Research Objectives

DoD systems require access to advanced electronic technologies, but it is difficult to qualify these technologies because of limited operational data and the complexity of the failure modes. Conventional reliability quantification methods are based on accelerated testing (with the acceleration typically provided by high temperature or bias), but these methods require understanding of the physical mechanisms responsible for device degradation to ensure that the same mechanisms are responsible for limiting the lifetime under both accelerated and normal operating conditions. Understanding the physics of failure in emerging technologies is thus a necessary condition for the deployment of these technologies in future DoD systems. This program conducted work to understand the physics of failure for emerging electronic technologies of particular significance to the DoD, with a focus on applications in a space environment. The specific technical areas we focused on are:

- (1) radiation effects in high speed devices and technologies and
- (2) reliability of GaN-based high electron mobility transistors (HEMTs).

Radiation effects are the key reliability challenge limiting the application of emerging technologies in space and defense systems. The radiation can be present naturally in the environment or be the result of a nuclear event. Radiation effects in electronics have been recognized as a critical problem in systems requiring high reliability for decades, but recent advances in semiconductor technology have dramatically affected the radiation-related vulnerabilities of electronic systems, as well as complicating testing and hardness assurance. These changes include the introduction of new materials (gate dielectrics, channel materials, metallization, isolation, and packaging), as well as new device structures (FinFETs, tri-gate transistors, HEMTs, trench-gate power devices, etc.).

Energy absorption, carrier generation, carrier transport, charge trapping and defect formation and dynamics depend, in part, on the specific materials used in the ICs. Sensitivity to the electrostatic effects of radiation-induced trapped charge, lifetime degradation, and device-edge and inter-device leakage depend on the detailed device geometries and doping profiles. Moreover, high-speed circuits exhibit increased vulnerabilities to single-event effects, including multiple-bit upsets that result from aggressive scaling, and large enhancements relative to ion-strike angle that are much greater than for earlier generations of technology. The complicated physical structure of modern

ICs, including many layers of metallization (e.g., 13 layers in Intel's 14-nm technology), makes it difficult to characterize radiation effects experimentally using typical radiation facilities or laser-test facilities. This program comprises work to explore the physics of failure in emerging technologies with applications in DoD/space systems and understand the physical mechanisms using new characterization techniques. It includes work to understand the relationship between radiation effects and bias effects in GaN-based HEMTs and exploration of new characterization techniques for understanding transient effects in emerging technologies.

Accomplishments

Significant progress was made related to the key technical areas mentioned above. Detailed results follow, but some of the key findings are summarized here:

- Vanderbilt upgraded its high-speed pulsed laser single-event effects test system with support from an Air Force-sponsored DURIP. This enabled testing over a broad range of laser wavelengths, which permits single-photon and two-photon absorption measurements to be made in a variety of materials, including wide bandgap semiconductors. This technique enabled important measurements to be performed on emerging high-speed technologies, as well as GaN-based HEMTs.
- The connection between radiation effects and reliability in GaN-based HEMTs was examined and explained. The combined effects of bias and radiation-induced defect formation were demonstrated, improving test and hardness-assurance techniques.
- Radiation effects in some of the most important and technologically significant emerging technologies were examined experimentally, using devices acquired through collaborations with the Interuniversity Microelectronics Center (imec). These devices represent some of the most advanced technologies available, allowing insight into the radiation tolerance of future generations of semiconductor devices.
- The radiation tolerance of CMOS technologies at very high dose levels was examined and explained. The work was based on devices intended for use in the large hadron collider at CERN and it provides important insight into how devices will respond in other challenging radiation environments.
- Changes in radiation tolerance of advanced CMOS technologies with continued scaling were explored and consolidated in forms that can be used to anticipate how future generations of technology can be used in DoD systems.
- Single-event transients in planar Si MOSFETs (28 nm and smaller) were characterized.
- Heavy-ion data from planar Si MOSFETs were compared to high-speed laser irradiation results. Multi-wavelength measurements were evaluated as a means of more closely approximating the physical mechanisms that dominate the heavy-ion response.
- Si-MOSFET single-event transient models were enhanced based on results of high-speed characterization.
- The single-event-transient responses of MOSFETs with channel materials other than Si were characterized. This work complemented a DTRA-funded 6.1 basic research program focusing on alternate-channel materials, including SiGe and Ge p-channel FinFETs and InGaAs n-channel FinFETs. The devices were fabricated at MIT and imec.
- Alternate-channel single-event transient data were compared to existing models and analyzed. These models are less mature than those for Si MOSFETs; consequently, both the

models and the characterization methods required refinement to obtain maximum benefit.

- High-speed laser characterization of compound-semiconductor-based HEMTs. Multiple wavelengths were evaluated to determine best practices for evaluating the single-event response of compound-semiconductor devices.
- High-speed laser testing of emerging device structures was performed. The devices were selected based on the most promising technologies, including nanowire FETs.
- Electrical stress effects on GaN HEMTs were examined. The stability of device current-voltage characteristics were determined as a function of bias and temperature for several device types.
- X-ray irradiation of GaN HEMTs was performed. Devices were irradiated with low-energy (10-keV) x-rays at various bias conditions. Since x-rays cannot displace atoms, these experiments provide information related to charge trapping and hydrogen release.
- Device simulation of GaN HEMTs was performed. The electrical effects of defects with characteristics corresponding to those obtained from experiments were simulated using TCAD tools (drift-diffusion) to understand effects of electrical stress and radiation on current-voltage characteristics. In addition, we explored the effects of defects on device operating parameters as a function of bias and temperature using ensemble Monte Carlo simulations that include the carrier-energy distribution.
- Proton-irradiation of GaN HEMTs was performed. Devices were irradiated with ~2-MeV protons at various bias conditions, including RF operating conditions. The protons produce ionization and displacement damage.
- Radiation effects on GaN HEMTs were characterized vs. temperature. While device degradation sometimes appears to be affected by RF bias conditions, it is difficult to determine if the differences between DC and RF bias are direct results of the bias or if they are indirect results of temperature differences.

1. Radiation effects in high speed devices and technologies

- 1.1. A tunable wavelength laser system and high-resolution transient capture system were developed to characterize transients in high-mobility MOSFETs. The experimental configuration enables resolution of fast transient signals and new understanding of charge collection mechanisms. The channel layer is critical in the charge collection process for the InGaAs FinFETs examined in this work. The transient current mainly comes from the channel current, due to shunt effects and parasitic bipolar effects, instead of the junction collection. The charge amplification factor is found to be as high as 14, which makes this technology relatively sensitive to transient radiation. The peak current is inversely proportional to the device gate length. Simulations show that the parasitic bipolar effect is due to source-to-channel barrier lowering caused by hole accumulation in the source and channel. Charge deposited in the channel causes prompt current, while charge deposited below the channel causes delayed and slow current.
- 1.2. The effects of total-ionizing-dose irradiation were investigated in HfO₂/InGaAs quantum-well MOSFETs. Radiation-induced hole trapping is higher for irradiation under positive gate bias than under negative gate bias. Electrical stress-induced electron trapping compensates radiation-induced hole trapping during positive gate-bias irradiation. Stress-induced hole trapping adds to the effects of radiation-induced hole trapping under negative gate bias. Radiation-induced charge trapping increases with the channel

- length.
- 1.3. We characterized the total-ionizing-dose response of strained Ge pMOS FinFETs built on bulk Si using a fin replacement process. Devices irradiated to 1.0 Mrad (SiO₂) show minimal transconductance degradation (less than 5%), very small V_{th} shifts (less than 40 mV in magnitude) and very little ON/OFF current ratio degradation (< 5%), and only modest variation in radiation response with transistor geometry (typically less than normal part-to-part variation). Both before and after irradiation, the performance of these strained Ge pMOS FinFETs is far superior to that of past generations of planar Ge pMOS devices. These improved properties result from significant improvements in processing technology, as well as the enhanced gate control provided by the strained Ge FinFET technology.
 - 1.4. The single-event-transient response of InGaAs FinFETs with different fin widths was examined using pulsed-laser and heavy-ion irradiation. Devices with wider fins collected more charge in both environments. Quantum-well structures confine charge collection in the channel and determine the sensitive volume. Simulations show that the charge density produced by irradiation is similar for devices with different fin widths, but more charge is collected by wider fin devices due to the larger channel volume. Charge accumulated in the buffer and substrate layers modulates the body potential, altering the degree of effective back-gate control, leading to additional effects associated with charge accumulation in wider fin devices. Optical simulations for a model system suggest that optical phenomena in the fins should be considered for laser testing. These include optical interference, plasmonic enhancement at the metal-dielectric interfaces, and enhanced electron-hole pair recombination due to multiple reflections in non-planar devices with nanoscale dimensions.
 - 1.5. The degradation induced by ultrahigh total ionizing dose was examined in 65-nm MOS transistors and found to be strongly gate-length dependent. The current drive decreases during irradiation, and the threshold voltage often shifts significantly during irradiation and/or high-temperature annealing, depending on transistor polarity, applied field, and irradiation/annealing temperature. Ionization in the spacer oxide and overlying silicon nitride layers above the lightly doped drain extensions leads to charge buildup as well as the ionization and/or release of hydrogen. Charge trapped in the spacer oxide or at its interface modifies the parasitic series resistance, reducing the drive current. The released hydrogen transports as H⁺ with an activation energy of ~0.92 eV. If the direction of the electric field is suitable, the H⁺ can reach the gate oxide interface and de-passivate Si-H bonds, leading to threshold voltage shifts. Newly created interface traps are most prominent near the source or drain. The resulting transistor responses and defect-energy distributions often vary strongly in space and energy as a result, as demonstrated through current-voltage, charge-pumping, and low-frequency noise measurements.
 - 1.6. The pulsed-laser single-event transient response of InGaAs FinFETs on bulk silicon substrates was investigated. Charge collection due to a source-drain shunt effect and drain-to-substrate junction charge collection contribute to the observed transients. The transient response of these silicon substrate devices is compared to that of InGaAs FinFETs on semi-insulating substrates. Faster transients with reduced peak currents and peak widths are observed on the silicon substrate devices. Simulations show hole collection by the silicon substrate. This reduces the amount of source-barrier lowering and

- bipolar-amplification relative to other III-V devices. Moreover, the reduced hole lifetime in the GaAs buffer layer also contributes to the relative reduction of the bipolar amplification in these devices.
- 1.7. We evaluated the total ionizing dose (TID) responses of InGaAs nMOS FinFETs with different gate lengths irradiated with 10-keV X-rays under different gate biases. The largest degradation after irradiation occurs at $V_G = -1$ V. Radiation-induced trapped positive charge dominates the TID response of InGaAs FinFET transistors, consistent with previous results for InGaAs multifin capacitors. Shorter gate-length devices show larger radiation-induced charge trapping than longer gate-length devices, most likely due to the electrostatic effects of trapped charge in the surrounding SiO₂ isolation and SiO₂/Si₃N₄ spacer oxides. The $1/f$ noise measurements indicate a high trap density and a nonuniform defect-energy distribution, consistent with a strong variation of effective border-trap density with surface potential.
 - 1.8. A commercial 65-nm CMOS technology was irradiated at ultrahigh ionizing doses and then annealed at high temperature under different bias conditions. The experimental results demonstrate the high sensitivity of pMOSFETs to radiation-induced short-channel effects, related to the buildup of defects in spacer dielectrics. We find that the charge buildup in the spacers is insensitive to the applied source-to-drain electric field, but the generation and/or annealing of interface traps strongly depends on applied drain bias and channel length. The static dc and charge-pumping measurements indicate a high density of interface traps in the lateral source/drain extension regions. The worst-case bias condition corresponds to the application of a large drain-source voltage, due to the lateral electric field driving hydrogen from the spacers toward the source extension and the channel. The consequent differences in growth and annealing rates of interface traps lead to a large asymmetric degradation of the short-channel transistors. The technology computer-aided design simulations are used to qualitatively confirm the proposed degradation model.
 - 1.9. 1.8-MeV proton irradiation to a fluence of $10^{14}/\text{cm}^2$ was found to not significantly affect the resistance or low-frequency noise of copper or ruthenium resistors fabricated via modern microelectronic fabrication techniques used to form metal lines. The room-temperature noise of these Cu and Ru resistors is surprisingly similar to that of Cu and Pt metal lines and wires fabricated using late-1970s nanofabrication techniques; however, measurements of the temperature dependence of the noise show that the defect kinetics are quite different among the various materials. A large increase in the noise magnitude observed above 200 K in Cu but not in Ru is consistent with the superior resistance to electromigration that Ru lines have shown, relative to Cu.
 - 1.10. We found that charge-density-wave devices with quasi-two-dimensional 1T-TaS₂ channels show remarkable immunity to bombardment with 1.8 MeV protons to a fluence of at least $10^{14} \text{ H}^+ \text{ cm}^{-2}$. The current-voltage characteristics of these devices do not change as a result of proton irradiation, in striking contrast to most conventional semiconductor devices or other two-dimensional devices. Only negligible changes are found in the low-frequency noise spectra. The radiation immunity of these “all-metallic” charge-density-wave devices is attributed to the quasi-2D nature of the electron transport in the nanoscale-thickness channel, high concentration of charge carriers in the utilized charge-density-wave phases, and two-dimensional device design. Such devices, capable of operating over a wide temperature range, can constitute a crucial

segment of future electronics for space, particle accelerator and other radiation environments.

- 1.11. A temperature-switching irradiation (TSI) sequence was developed based on a first-principles understanding of interface-trap buildup and annealing. The dynamics of interface-trap buildup and annealing during elevated temperature irradiation are described in detail to provide background, context, and enhanced understanding of the TSI method. The method is shown to be a practical and conservative test for enhanced low-dose-rate sensitivity (ELDRS) in linear bipolar devices and ICs. Examples of TSI sequences are shown for target doses up to 200 krad(Si), a range of great practical interest for space applications. The method can be adapted for higher dose applications via similar approaches. Devices that do not exhibit ELDRS respond similarly to TSI and high-dose-rate irradiation.
- 1.12. The general reduction in the thicknesses of critical dielectric layers driven by Moore's law scaling has led to increasingly more manageable total-ionizing-dose (TID) response over the last ~50 years. Effects of oxide, interface, and border traps in MOS gate oxides on TID response are now mostly well known for SiO₂ gate dielectrics, and the leakage currents due to isolation oxides can be conservatively bounded with existing test methods. Radiation hardened and/or radiation-tolerant technologies have been developed that can survive doses that exceed 1 Mrad(SiO₂). Advances in computing technology enabled by Moore's law scaling and concomitant enhancements in computational techniques have greatly facilitated the modeling and simulation of TID effects in microelectronic devices and ICs. However, the TID response of nanoscale MOS devices with advanced gate stacks and high-K gate dielectrics, and/or alternative materials to Si, is often more complex than for MOS devices with SiO₂ gate oxides. TID challenges remain for linear bipolar technologies that exhibit enhanced low-dose-rate sensitivity and for microelectronic devices that must function at doses above ~100 Mrad(SiO₂), e.g., in high luminosity accelerator environments. TID effects have also recently been observed in wide bandgap semiconductor devices (e.g., GaN/AlGaN HEMTs) with no gate oxide.
- 1.13. Total ionizing dose effects were investigated on a physically unclonable function (PUF) based on CMOS breakdown. Devices irradiated to 2 Mrad(SiO₂) show less than 11% change in current ratio at 1.2 V. The read-out window of programmed PUFs decreases significantly at high-dose proton irradiation, and then recovers back to the original value after annealing. The proton test results for the *p*FET selector, the *unbroken n*FET, and the *broken n*FET indicate that the threshold-voltage shift of the *p*FET selector contributes mainly to the degradation of the PUF.
- 1.14. The radiation response of complementary metal-oxide-semiconductor (CMOS) gate oxides is typically insensitive to true dose-rate effects, but damage in deep-sub-micrometer technologies is dominated by ionization mechanisms in thick isolation oxides surrounding the transistors. Recent results in 65-nm FETs demonstrated that performance degradation in ultrahigh total ionizing dose (TID) experiments is due to defects in the isolation shallow trench isolation oxide or in the materials composing the lightly doped drain spacers. These insulators are thick, deposited, and crossed by a low electric field, characteristics similar to those typical of passivation oxides in linear bipolar technologies for which an enhanced low-dose-rate sensitivity (ELDRS) has been observed and systematically studied. We report in this paper the clear evidence of a dose-rate

- sensitivity of the TID-induced damage in both 130 and 65-nm CMOS technologies exposed to different radiation sources (X-rays and γ -rays from a 60 Co source). This sensitivity is attributed to mechanisms similar to those explaining ELDRS in bipolar devices and represents a significant challenge to the definition of a qualification procedure for circuits to be used in extreme radiation environments.
- 1.15. The thermalization process of sub-10-eV charge carriers was examined by treating carrier transport with full-band Monte Carlo simulations. The average energy loss (3.69 eV in Si and 2.62 eV in Ge) required to create a thermalized electron-hole pair, obtained from the simulations, is very close to the experimentally measured radiation-ionization energies of Si and Ge irradiated with high-energy particles. These results suggest that only interactions that occur after the radiation-generated charge carriers decay to energies of ~ 10 eV or less determine the fundamental property of the radiation-ionization energies. In addition to an energy loss equal to the band gap energy via impact ionization, acoustic-phonon emission, which has been omitted in prior work, contributes 30% of the remaining carrier energy loss, while optical-phonon emission contributes the other 70%.
 - 1.16. We evaluated the total-ionizing-dose (TID) responses of InGaAs nMOS fin field-effect transistors (FinFETs) with a modified gate-stack irradiated with 10-keV X-rays under different gate biases. This modified InGaAs nMOS FinFET process shows decreased subthreshold leakage current and increased hysteresis in as-processed devices, and reduced hole trapping in irradiated devices, compared to first-generation development-stage devices. The reduction in subthreshold leakage current is attributed to changing the buffer layer from GaAs to $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$, thereby enhancing the material quality. Both the increased hysteresis in as-processed devices and reduced hole trapping in irradiated devices are attributed primarily to thinning the Al_2O_3 layer that separates the HfO_2 from the InGaAs layers. This facilitates charge exchange with defects at the $\text{HfO}_2/\text{Al}_2\text{O}_3$ interface and reduces the percentage of radiation-induced holes that are generated in the Al_2O_3 and trapped in the HfO_2 . The removal of a tungsten layer above the TiN gate reduces the interface dose enhancement.
 - 1.17. We experimentally found that pulsed, laser-induced, single-event current measurements on silicon-on-insulator (SOI) FinFETs at subbandgap wavelength (1260 nm) are affected by the polarization of the laser light used in the experimental testing setup. Such polarization dependence is not observed during pulsed laser, single-event effects testing on large-area silicon diodes, suggesting that polarization dependence arises due to the presence of the nanoscale fin. Plasmonic enhancement is proposed as a likely mechanism for the polarization effects due to the metal/dielectric interfaces in the fin region. The observed polarization dependence has ramifications for collection and interpretation of data acquired by pulsed laser testing. Device orientation of FinFETs and other nanoscale devices during pulsed laser testing should be considered in order to ensure consistent testing conditions and reproducible measurement results across multiple measurement campaigns.
 - 1.18. A sensitive volume was developed using pulsed laser-induced collected charge for two bias conditions in an epitaxial silicon diode. These sensitive volumes show good agreement with the experimental two-photon absorption laser-induced collected charge at a variety of focal positions and pulse energies. When compared to ion-induced collected charge, the laser-based sensitive volume overpredicts the experimental collected charge

- at low bias and agrees at high bias. A sensitive volume based on ion-induced collected charge adequately describes the ion experimental results at both biases. Differences in the amount of potential modulation explain the differences between the ion- and laser-based sensitive volumes at the lower bias. Truncation of potential modulation by the highly doped substrate, at the higher bias, results in similar sensitive volumes.
- 1.19. Total-ionizing-dose (TID) effects and low-frequency noise were evaluated in 30-nm gate-length bulk and silicon-on-insulator (SOI) FinFETs for devices with fin widths of 10-40 nm. Minimal threshold voltage shifts are observed at 2 Mrad(SiO₂), but large increases in low-frequency noise were found, and significant changes in defect-energy distributions were inferred. Radiation-induced leakage current is enhanced for narrow- and short-channel bulk FinFETs. Short-channel SOI FinFETs show enhanced degradation compared with longer-channel devices. Narrow- and short-channel SOI devices exhibit high radiation tolerance. Significant random telegraph noise (RTN) is observed in smaller devices due to prominent individual defects.
 - 1.20. Total-ionizing-dose mechanisms were investigated in 16-nm InGaAs FinFETs with an HfO₂/Al₂O₃ gate-stack. Transistors were irradiated up to 500 krad(SiO₂) and annealed at high temperatures. Irradiated devices show negative threshold-voltage V_{th} shifts, sub-threshold stretch-out, and leakage current increases. These result from positive charge trapping in the gate oxide and shallow trench insulators, and increases in the interface and border-trap charge densities. Low-frequency noise measurements at different temperatures indicate a significant increase of noise magnitude in irradiated devices at an activation energy of ~0.4 eV. Density functional theory (DFT) calculations strongly suggest that transistor V_{th} shifts are due primarily to hole trapping at oxygen vacancies in the HfO₂, and the increased noise is due primarily to O vacancies in the Al₂O₃. Additional contributions to the noise from defects in the GaAs buffer layer are also likely, primarily at low temperatures.
 - 1.21. The total-ionizing-dose (TID) response of indium gallium arsenide (InGaAs) MOSFETs with Al₂O₃ gate dielectrics and several channel lengths was evaluated under different biases. DC static characteristics showed large negative threshold voltage V_{th} shifts and subthreshold stretchout (SS), indicating net positive charge trapping in the gate oxide and generation of the interface and border traps. Hysteresis and $I_d - V_{gs}$ measurements from cryogenic to high temperatures show the important role of defects in the Al₂O₃ gate dielectric to the TID response. Radiation-induced-hole trapping is attributed to oxygen vacancies in the Al₂O₃. The relatively large hysteresis in these devices is attributed primarily to dangling Al bonds in the near-interfacial Al₂O₃. Analysis of the temperature dependence of V_{th} and SS suggests that the rate at which electrons leave the Al₂O₃ during a positive-to-negative gate-bias sweep is higher than the rate at which they enter during a negative-to-positive gate-bias sweep.
 - 1.22. The total-ionizing-dose response of few layer MoS₂ transistors with ZrO₂ or h-BN gate dielectrics was investigated under various bias conditions. Defects in MoS₂ and surrounding dielectric layers significantly affect radiation-induced trapping. For devices with ZrO₂ dielectrics, much larger negative V_{th} shifts and peak transconductance degradation are observed for irradiation under negative and ground bias than under positive bias. The h-BN devices exhibit positive threshold voltage shifts under negative-bias irradiation. For both ZrO₂ and h-BN passivated devices, the peak transconductance degradation results from charge trapping at the surface of the MoS₂ or in nearby oxides.

- Changes in defect energy distributions of MoS₂ FETs during X-ray irradiation are characterized via temperature-dependent low-frequency noise measurements. Density functional theory calculations are performed to provide insight into the pertinent defects.
- 1.23. Laser-induced single-event transients (SETs) were observed in black phosphorus (BP) MOSFETs. The SETs are relatively small, which is consistent with expectations for thin-film fully depleted transistors. The position dependence and the bias-dependence of the measured SETs in BP transistors are investigated to study the charge collection mechanisms. The peak drain current is maximized when the pulsed-laser strikes at the center of the channel region. The amplitudes of the SETs are also relatively independent of the overdrive voltage. The drain-to-source SET current increases when $|V_{DS}|$ increases, due to a shunt effect.
 - 1.24. We found that the peak transient currents due to pulsed-laser or heavy-ion irradiation of Ge *p*MOS FinFETs are nearly independent of gate bias. This is because the prompt photocurrent is due primarily to a transient source–drain shunt. In contrast, long-term diffusion charge collection is strongly gate-bias dependent. This bias dependence results from hole injection from the source in response to the transient increase in electron concentration in the channel. The transients measured at the source terminal change polarity when the strike location moves from the source to the drain, but this effect does not occur for the transients measured at the drain terminal. Charge collection mechanisms are studied using TCAD simulations.
 - 1.25. Heavy-ion, focused X-ray, and pulsed laser single-event transient (SET) experiments were performed on a silicon epitaxial diode. Collected charge, transient rise times, and transient fall times are calculated and compared between different sources. The transient shape characteristics depend on the source (ion, X-ray, or laser), even when similar amounts of charge are generated. The observed differences are examined and explained in terms of basic charge collection mechanisms.
 - 1.26. Single-event upsets were observed in a 72-layer 3-D NAND flash memory operated in a single-level cell mode after low-energy proton (500 keV–1.2 MeV) and heavy-ion irradiation. The layer-by-layer error count was analyzed to visualize the stopping of low-energy protons within the memory stack, and Monte Carlo simulations are correlated with the experimental data. Direct ionization by low-energy protons is identified by 3-D data analysis and the energy dependence of device-sensitive cross section.
 - 1.27. We provided insights into the kinetics and energetics of interface-trap annealing. Interface traps in MOS and linear bipolar devices anneal much more easily at 0 V bias than at positive or negative applied bias. Hydrogen transport and reactions play critical roles in interface-trap buildup and annealing processes. The complex interplay between H₂ diffusion and H⁺ drift was illustrated via coupled experimental and theoretical studies. Interface-trap annealing imposes significant constraints on hardness-assurance techniques. Current MOS standard tests that incorporate accelerated aging at elevated temperature at worst case, static, positive bias enable successful assessment of MOS devices in low-dose-rate environments. However, it is not similarly possible to use elevated-temperature irradiation and/or annealing at worst case, 0 V bias to predict low-dose-rate response for linear bipolar devices and ICs. Temperature-switching during irradiation appears to be a promising approach to address this issue.
 - 1.28. We showed that MOS total-ionizing-dose (TID) response is affected strongly by size scaling and the migration from planar to three-dimensional architectures. Radiation-

- induced charge trapping in isolation oxides and/or charge transport from surrounding materials are critical to the TID response of nanoscale MOS devices. As transistor dimensions and operating voltages have decreased, single-event effects due to cosmic rays and high-energy protons in space and neutrons in terrestrial environments have become increasingly significant to the radiation response of MOS devices. However, nanoscale MOS transistors are essentially immune to ion-induced gate rupture at normal operating voltages. Single particle interactions will become even more important for future, ultimately scaled MOS devices used in classical and quantum computing applications.
- 1.29. We examined the foundations of Shockley's equation for the average electron-hole pair creation energy, which is very important for relating the energy deposited by incident radiation to device response. Energetic carriers in semiconductors thermalize by impact-ionization, which generates electron-hole pairs (EHPs), and by energy losses to phonons. The average EHP creation energy is typically about three times the energy gap. In 1960, Shockley derived a simple equation for the average EHP creation energy with a single free parameter that fits experimental values for a wide range of materials, but the underlying assumptions have been widely criticized as lacking justification. Modified expressions derived by improved approximations have been proposed but do not fare better. We examined the foundations of Shockley's equation and provided a robust justification for the kinetic-energy component as a model averaging procedure and then applied a similar procedure to the phonon component of the equation. The phonon result retains Shockley's form, but the interpretation and justification are now on par with those of the kinetic-energy term. The single-parameter fit to the data remains unchanged, i.e., the present analysis accounts for the exceptional applicability of Shockley's equation.
 - 1.30. Total-ionizing-dose (TID) effects were investigated in a highly-scaled gate-all-around (GAA) FET technology using Si nanowire channels with a diameter of 8 nm. n- and p-FETs were irradiated up to 300 Mrad(SiO₂) and annealed at room temperature. TID effects are negligible up to 10 Mrad(SiO₂). At ultrahigh doses, the TID degradation depends on the irradiation bias condition, with more severe effects observed in longer channel devices. The worst case irradiation condition is when positive bias is applied to the gate. Threshold-voltage shifts are caused by H⁺-driven generation of interface traps at the oxide/channel interface. In contrast, FETs irradiated under negative gate bias are dominated by transconductance loss and increases of low-frequency noise, suggesting the activation of border traps. Enhanced off-leakage current is observed in n-FETs due to charge trapping in shallow-trench isolation, and in p-FETs due to trap-assisted recombination at STI sidewalls and/or spacer dielectrics at drain/bulk junctions.
 - 1.31. Negative-bias-stress and total-ionizing-dose (TID) effects in deeply scaled Ge-gate-all-around (GAA) nanowire (NW) devices were characterized for different biasing conditions. Negative-bias-stress-induced degradation in Ge GAA device originates primarily from the interface- and border-trap generation. Devices stressed at high gate voltage show rapid initial degradation and quick saturation dominated by interface-trap generation. Radiation-induced OFF-state leakage current in Ge GAA NWs increases with dose due to enhanced band-to-band tunneling (BTBT) caused by charge trapping in the shallow trench isolation (STI).

2. Reliability of GaN-based high electron mobility transistors (HEMTs)

- 2.1. We found that the low-frequency $1/f$ noise of AlGaN/GaN HEMTs before and after 1.8-MeV proton irradiation is more consistent with a carrier-number fluctuation model that includes a non-constant defect-energy distribution $D_t(E_f)$ than with the Hooge mobility fluctuation model. A strongly varying $D_t(E_f)$ in these devices was confirmed by measurements of the voltage and temperature dependence of the noise. First-order estimates of effective border-trap density before and after 1.8-MeV proton irradiation are obtained for commercial and research-grade devices using a simple number-fluctuation model. The input-referred noise magnitude of GaN/AlGaN HEMTs decreases at biases that are much more positive than threshold because the gated region of the HEMT comprises a relatively small portion of the channel, and the noise is attenuated by the voltage divider formed by the gated and ungated regions of the channel.
- 2.2. Responses to 1.8 MeV proton irradiation and 10-keV X-ray irradiation under typical bias conditions were investigated for AlGaN/GaN HEMTs fabricated with different types of process technologies. We found that, in contrast to previous generations of process technologies, total ionizing dose effects can be significant in these devices. For proton irradiation, worst-case bias for transconductance degradation for GaN-on-SiC substrate devices is ON bias, and for devices built on free-standing GaN substrates, the worst-case bias condition is semi-ON bias. Low-frequency noise measurements demonstrate that these differences result from differences in defect types and energy distributions for the different types of devices, both before and after irradiation. These results emphasize the need to test devices under a wide range of conditions during characterization and qualification testing.
- 2.3. Significant threshold voltage V_{th} shifts were observed during 10-keV X-ray irradiation of AlGaN/GaN high-electron mobility transistors (HEMTs). Shifts are much smaller for lower dose-rate Cs-137 irradiation than that for higher dose-rate X-ray irradiation. This occurs because hydrogen transport and interactions with defects and impurities in these crystalline wide bandgap semiconductor materials differ fundamentally from those in amorphous SiO₂. The electric field is also higher in GaN-based HEMTs than in bipolar base oxides. The absence of enhanced low-dose-rate sensitivity in these devices simplifies testing of GaN-based HEMTs for space applications. No significant X-ray-induced V_{th} shifts are observed in development stage InAlN/GaN HEMTs.
- 2.4. Gate and drain bias dependences of hot carrier degradation were evaluated for AlGaN/GaN HEMTs fabricated via two different process methods. Both positive and negative threshold voltage V_{th} shifts were observed for each device type, depending on the mode and duration of the stress, indicating the presence of significant densities of donor-like and acceptor-like traps. Worst-case stress bias for transconductance degradation is the “ON” state for both device types. We found that transconductance degradation provides a more effective parameter to monitor defect buildup than V_{th} shifts, and that a single worst-case stressing bias condition cannot be defined for all varieties of AlGaN/GaN HEMTs. Low-frequency noise measurements versus temperature assist the identification of defects responsible for the observed degradation. Defect dehydrogenation and oxygen impurity centers are found to be particularly significant to the response of these devices.

- 2.5. We conducted a comprehensive investigation of the electron transport properties of wurtzite-phase GaN and AlN and of an Al_{0.25}Ga_{0.75}N/GaN HEMT by solving the Boltzmann transport equation with a synchronous ensemble Monte Carlo technique and employing first-principles electronic properties, including the full energy bands, phonon dispersions, and electron-phonon scattering rates. We found that, for electron collisions with the highest-energy optical phonon mode, nonpolar scattering by optical phonons contributes comparable to polar scattering. Polar scattering with acoustic phonons, that is, piezoelectric scattering, is found to be as important as the polar scattering with optical phonons for low-energy electrons at room temperature. We compared the calculated high-field transport characteristics of bulk GaN with previously reported results. We also calculated the nonpolar acoustic deformation potential, nonpolar optical deformation potential, and high-field transport characteristics of bulk AlN. We found that inclusion of piezoelectric scattering results in a low-field electron mobility of approximately 450 cm²/(V s), which is very close to the experimental value. Simulation results are presented for an Al_{0.25}Ga_{0.75}N/GaN HEMT, including electric field, average carrier kinetic energy, and drift velocity in the channel. We obtained the carrier energy distribution function in the conducting channel, which is key to accurately determine hot-carrier-caused device degradation and identify possible routes to improved device designs.
- 2.6. In collaboration with AFRL, the effects of high-field stress were evaluated for industrial-quality AlGaIn/GaN HEMTs as a function of bias and temperature. Positive and negative threshold voltage shifts were observed, depending on stress conditions, indicating the presence of acceptor-like and donor-like traps in these devices. Worst-case transconductance degradation under rated device operating conditions was observed for devices subjected to high-voltage stress in the ON bias condition at elevated temperature. This contrasts with results on earlier-generation devices, which often show worst-case response under semi-ON bias conditions, emphasizing that each technology requires characterization under multiple bias-stress conditions. Neutral and charged oxygen donor-like DX centers and substitutional acceptor-like N_{Ga} centers are the dominant defects contributing to low-frequency noise in these devices. Dehydrogenation of O_N-H complexes during O_N-bias stress and the resulting increases in densities of O_N-related donorlike defects are evidently the reliability-limiting mechanism in these devices.
- 2.7. Charge transport mechanisms of forward and reverse leakage currents in vertical GaN Schottky barrier diodes were investigated by measuring the temperature-dependent current-voltage characteristics. The results show that the leakage current is primarily governed by dislocation-associated thermionic field emission (TFE). The primary transport path is the reduced, localized conduction band around the dislocation core rather than the continuum defect states. A refined phenomenological physical model is developed for conductive dislocations in GaN, emphasizing that: 1) surface donors, surrounding the core of dislocations, can significantly shrink the barrier region after ionization, causing severe TFE leakage; 2) the ON donors likely to be responsible for TFE have a typical density of $\sim 1 \times 10^{18}$ cm⁻³ at 300 K and activation energy of 78 meV; and 3) the barrier height at donor sites is ~ 0.65 eV at 300 K, which is reduced by ~ 0.4 eV with respect to the dislocation-free region.
- 2.8. We reviewed the atomistic processes that lead to the dehydrogenation of Si-H at the

critical Si/SiO₂ interface of Si MOS devices and of O-H complexes in GaN and GaAs. The resulting increases in activated interface and bulk defect densities can shift device threshold voltages and/or degrade transconductance and carrier lifetimes.

- 2.9. We summarized displacement damage (DD) effects, total-ionizing-dose (TID) effects, and single-event effects in AlGaIn/GaN high electron mobility transistors (HEMTs). High-fluence proton-induced DD creates point defects and impurity complexes at fluences that are comparable to or higher than those encountered in space applications. Defect and impurity dehydrogenation also contributes significantly to the DD/TID response at fluences typical of realistic space environments. The bias applied during irradiation can affect the DD/TID response strongly. Bias stress before irradiation can lead to enhanced proton-induced degradation of AlGaIn/GaN HEMTs. Low-frequency noise measurements and density functional calculations provide insight into defect microstructures and energy levels. GaN-based HEMTs can be quite vulnerable to single-event effects in space. Of particular concern is single-event burnout (SEB). The vulnerabilities of GaN-based devices to SEB at voltages below rated limits and significant device-to-device variations in SEB response lead to significant voltage derating for GaN-based power devices in space systems. Developing an improved understanding of the effects of defects and hydrogen on the radiation response of AlGaIn/GaN HEMTs can improve the DD/TID response by reducing threshold-voltage shifts and transconductance degradation. Reducing defect densities may also reduce the variation in SEB response, enabling reliable device operation at higher voltages in future space systems.

Dissemination of results

The work resulted in multiple publications, as detailed in Section 1 of this report (reported through the structured input section of the web reporting form). Many of the PIs and graduate students working attended the IEEE Nuclear and Space Radiation Effects Conference each year, which was held virtually in 2020 and 2021. The conference took place in person in 2018, 2019, and 2022.

The Vanderbilt HiREV investigators also participated in the weekly SCALE zoom meetings that are conducted for students at participating universities and government sponsors. These meetings are organized by Mike Alles, one of the Vanderbilt co-investigators.

Plans

Nothing to report. This is the final report.

Impacts

Development of the principal discipline(s) of the project

This work provided understanding of how state-of-the-art electronic devices will perform in space, where they are exposed to energetic particles. This space radiation affects the reliability of electronics, by degrading the device operation and possibly changing the information and results. The results are especially important for high-speed devices, which enable sophisticated processing in space.

Other disciplines

The results of this work are important for systems designers, who need information and estimates of error rates and reliability to determine whether their systems will operate as intended in space.

Impact on teaching and educational experiences

The participants in this program also contribute to the Scalable Asymmetric Lifecycle Engagement (SCALE) program. This is a DoD-funded workforce development program led by Purdue University. Vanderbilt leads the radiation effects component of the SCALE program. It has had a significant impact on the number of students who choose to go into the radiation-effects field, with multiple students participating in internships at DoD facilities to at companies that are part of the defense industrial base.

Impact in this reporting period on physical, institutional, and information resources that form infrastructure.

Much of the work conducted through this program was related to development of high-speed single-event-effects characterization techniques utilizing pulsed laser testing. The equipment was upgraded through an AFOSR-sponsored DURIP program and the methods of applying the system were strongly impacted by this program.

The pulsed laser system is a titanium-sapphire (Ti/S) pumped Optical Parametric Generator (Topas- 4/800, Light Conversions, Lithuania). The OPG is pumped at 1kHz repetition rate with 1 mJ, 150 fs pulses centered at 800 nm from a chirped-pulse amplifier (Titan- I, Quantronix). The amplifier is seeded with a passively mode-locked Ti/S oscillator (Mira 900, Coherent). The Topas uses non-linear parametric frequency conversion in a BBO crystal to generate and amplify signal and idler wavelengths that are continuously tunable from ~1200nm to ~2400nm. Using harmonic, sum, and difference frequency generating crystals outside the OPG, wavelengths from ~200nm to ~10 μ m can be generated with average pulse energies that vary from 1 μ J/pulse to 100 μ J/pulse, depending on the wavelength. A prism is used to isolate the desired wavelength from the output of the laser system. Optics currently installed on the beam line allow for component testing at wavelengths from 300nm to 2600nm. The selected wavelength is spatially filtered and variably attenuated using holographic wire-grid polarizers before reaching the test bench. The laser beam passes through a series of beam splitters before reaching the target; the first beam splitter diverts a fraction of the beam to a calibrated photodetector (Electro-Optics Technology); each pulse from the detector is captured and measured individually. Another beam splitter couples a broadband near-IR light source onto the beam axis for illuminating the target, and another sends light reflected from the target to an IR camera for imaging and positioning of the laser spot. Finally, the laser is focused on the target using either a 50X or 100X microscope objective mounted to a customized high-precision z-stage used to change the depth at which the laser focuses inside the die. The target is mounted to a mechanical x-y stage that can scan the die over the focused laser spot in 100nm steps. Automated scanning routines can perform line scans, area scans in the *x-y*, *x-z*, and *y-z* planes, and volumetric scans.

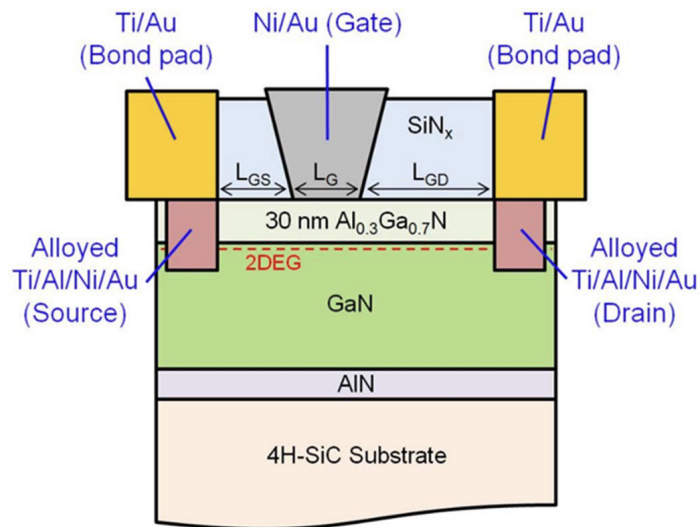
Changes

The work was conducted as proposed. This is the final report and no additional changes will be

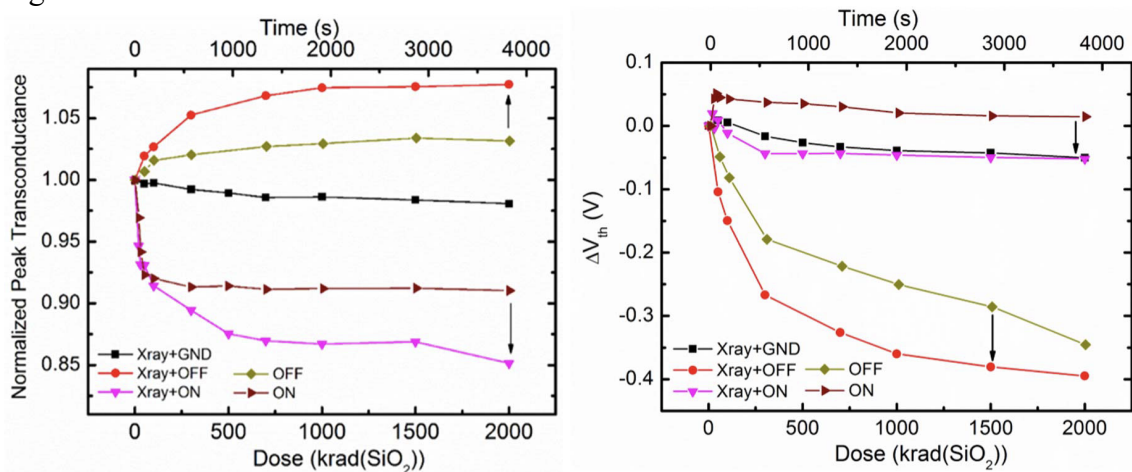
made.

Technical Updates

This program made significant progress on topics related to radiation effects and reliability of emerging technologies and GaN-based HEMTs. A cross-section of one of the GaN HEMTs examined here follows.

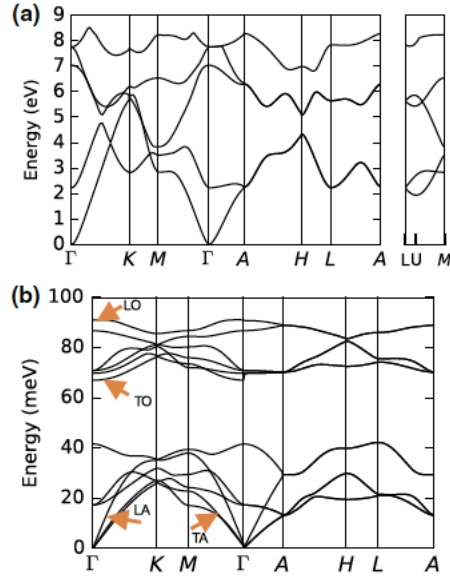


We found that the peak transconductance and threshold voltage of these devices degrade due to ionizing radiation, as expected, but that the amount of degradation depends on the bias condition. This was a surprising result and one that has important consequences for hardness assurance testing.

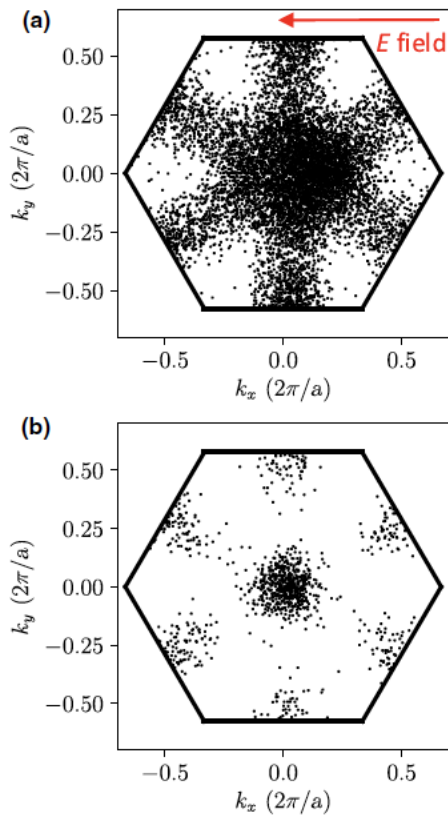


We analyzed radiation effects and reliability using full-band Monte Carlo transport simulations of the HEMTs. Operating under large bias and electric fields, hot electrons are present in the channel where they can activate preexisting benign defects that cause scattering or carrier trapping, resulting in device degradation, such as threshold-voltage shifts and transconductance

degradation. We solved the Boltzmann transport equation with a synchronous ensemble Monte Carlo technique and employed first-principles electronic properties, including the full energy bands, phonon dispersions, and electron-phonon scattering rates. This is a very challenging problem and it required substantial modification of an existing transport code. The energy bands used in the simulations (a) and the phonon dispersion relation (b) are shown here.



The distribution of the electrons in the energy bands at an electric field of 800 kV/cm follows.



A histogram of the carrier energy distribution can be obtained, which we showed can be related to the device degradation.

