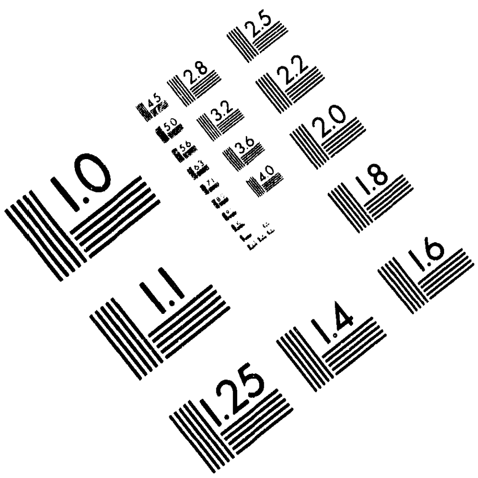

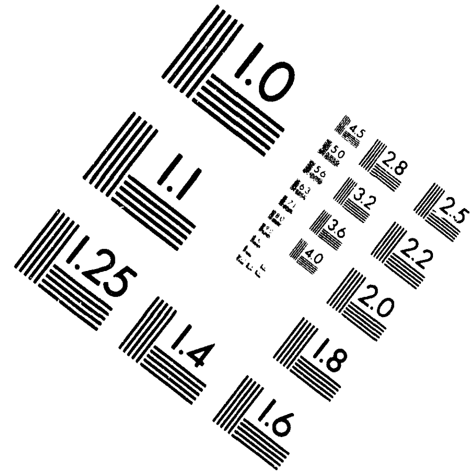

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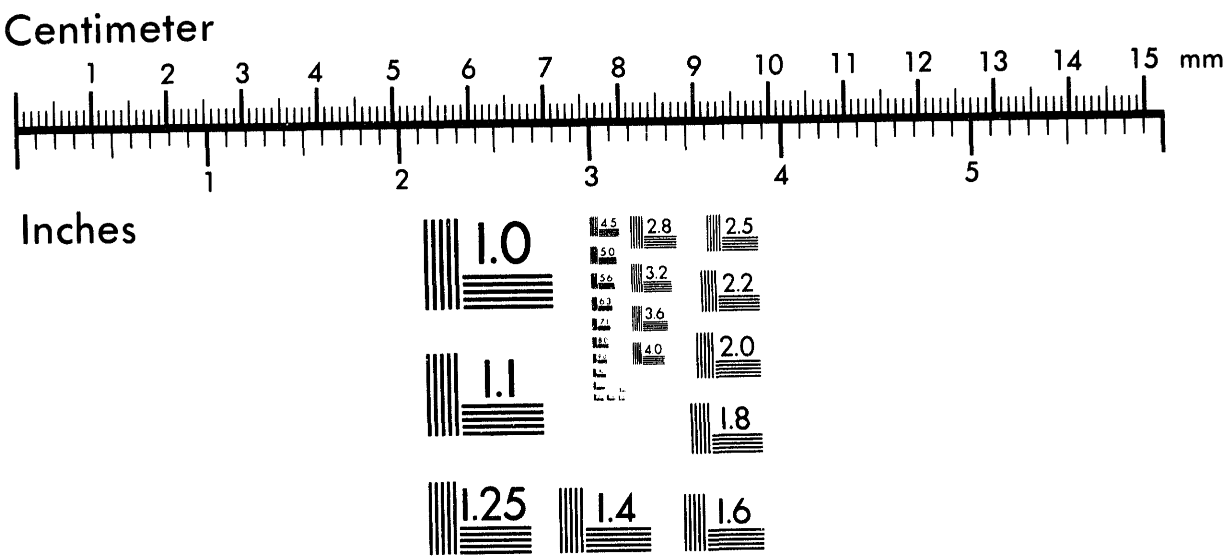

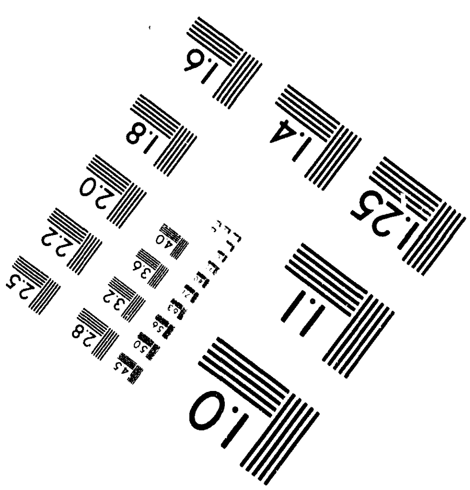

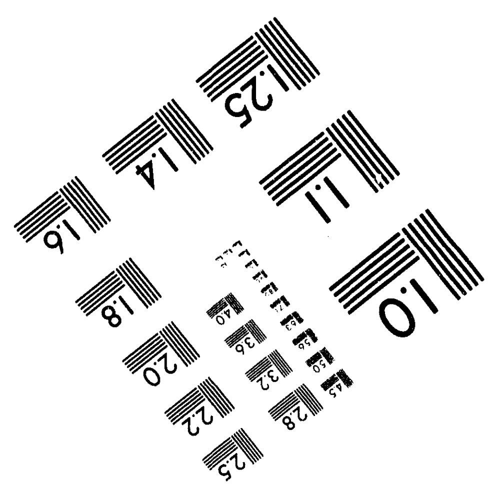

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PROTON IRRADIATION EFFECTS ON ADVANCED DIGITAL AND MICROWAVE III-V COMPONENTS*

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Abstract

A wide range of advanced III-V components suitable for use in high-speed satellite communication systems were evaluated for displacement damage and single-event effects in high-energy, high-fluence proton environments. Transistors and integrated circuits (both digital and MMIC) were irradiated with protons at energies from 41 to 197 MeV and at fluences from 10^{10} to $2x10^{14}$ protons/cm^2. Large soft-error rates were measured for digital GaAs MESFET ($3x10^{-5}$ errors/bit-day) and heterojunction bipolar circuits (10^{-5} errors/bit-day). No transient signals were detected from MMIC circuits. The largest degradation in transistor response caused by displacement damage was observed for 1.0-μm depletion- and enhancement-mode MESFET transistors. Shorter gate length MESFET transistors and HEMT transistors exhibited less displacement-induced damage. These results show that memory-intensive GaAs digital circuits may result in significant system degradation due to single-event upset in natural and man-made space environments. However, displacement damage effects should not be a limiting factor for fluence levels up to 10^{14} protons/cm^2 [equivalent to total doses in excess of 10 Mrad(GaAs)].

I. INTRODUCTION

The superior high-frequency properties of GaAs and other III-V components as compared to silicon components make them ideal for space communication systems. This is true for both microwave devices in transmit and receive circuitry and digital devices in high-speed communication circuitry. Devices in a space communication system can degrade due to the harsh radiation environments of both the natural and man-made space environments.

Natural and man-made space environments contain varying concentrations of electrons and protons. For the range of energies of electrons in space (up to ≤ 7 MeV) [1], electrons only interact through ionization effects in GaAs devices. Fortunately, GaAs devices are inherently hardened to ionizing radiation. Previous works have shown that GaAs devices can be irradiated with ionizing gamma radiation to levels in excess of 100 Mrad(GaAs) without significant degradation [2,3]. Thus, electron interactions are relatively unimportant in determining the radiation response of GaAs devices in either natural or man-made space environments.

Protons have higher energies in space (up to 400 MeV) and mass than electrons and can interact through both ionization effects and displacement damage. For the lower proton fluence levels of natural space environments, the primary effects of protons on GaAs devices are through single-event effects. Memory-intensive GaAs MESFET ICs have been shown to have soft error rates as high as 10^{-3} errors/bit-day due to the protons and heavy ions present in the natural space environment [4,5]. For the higher proton fluence levels of man-made space environments, both displacement damage and single-event effects can cause device degradation. Very little work has been performed on evaluating advanced III-V components (e.g. short gate length MMICs fabricated using HEMT transistors) used in present-day communication systems in high-energy, high-fluence proton environments.

For components to be employed in space systems, it is important to develop characterization data detailing

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Table 1: Devices evaluated during proton irradiations at Indiana University.

Device	Material	Features
14 Bit Counter	GaAs	Digital IC: 1.0-µm E/D MESFET Construction
128 x 16 Register File	GaAs/AlGaAs	Digital IC: HBT Construction
Voltage-Variable Attenuator	GaAs	MMIC: 0.5-µm Gate Length D-MESFET
Amplifier	GaAs	MMIC: 0.5-µm Gate Length D-MESFET
Frequency Doubler	GaAs	MMIC: 0.25-µm Gate Length D-MESFET
Low-Noise Amplifier	GaAs/AlGaAs	MMIC: 0.15-µm Gate Length PHEMT Transistors
Low-Noise Amplifier	GaAs/AlGaAs	MMIC: 0.1-µm Gate Length PHEMT Transistors
Transistors	GaAs/AlGaAs	PHEMT 0.1- and 0.15-µm Gate Length
Transistors	GaAs	MESFET 0.5-µm D and 1.0-µm E and D Gate Length

their characteristics in low and high fluence proton environments. In this paper, we evaluate the radiation response of a wide range of advanced GaAs and other III-V devices, suitable for use in communication satellite systems, for single event upset and displacement damage in proton environments.

II. EXPERIMENTAL DETAILS

A. Devices

A wide range of devices, manufactured by several different suppliers were evaluated. A complete list of these devices is given in Table 1.

Both digital integrated circuits and monolithic microwave integrated circuits (MMIC) were evaluated for single-event effects and displacement damage. Each type of integrated circuit was obtained from a different manufacturer. The digital circuits consisted of a 14-bit counter fabricated using enhancement/depletion-mode (E/D) 1.0-µm MESFET transistors and a 128x16 register file fabricated using heterojunction bipolar transistors (HBT). The 14-bit counter was designed and processed in a fully ion implanted MESFET process. Transistors were formed by implanting directly into a semi-insulating GaAs substrate and arranged in a source coupled FET logic (SCFL) configuration. The design and layout rules were 1 µm device feature size and two levels of interconnect metal on a ~3 µm pitch. The register files were designed and processed using GaAs/AlGaAs HBT transistors and utilizing resistor/transistor logic (RTL) in a current steering configuration. The design and layout rules were 1.25 µm device feature size and two levels of interconnect metal on a ~4 µm pitch. The MMIC circuits consisted of a voltage variable attenuator and an amplifier fabricated using depletion-mode 0.5-µm MESFETs, a frequency doubler fabricated using depletion-mode 0.25-µm MESFETs, and two low-noise amplifiers fabricated using 0.1- or 0.15-µm P-HEMTs.

Transistors were obtained from the same suppliers as the integrated circuits. They were fabricated identical to the transistors on the integrated circuits or taken directly off integrated circuit die. Thus, their radiation response is a good representation of the radiation response of the transistors located on the integrated circuits [6]. Transistors characterized included MESFET, P-HEMT, and HBT transistors. The MESFET transistors had gate lengths of 0.5 and 1.0 µm. For the 1.0-µm transistors both depletion- and enhancement-mode transistors were characterized and for the 0.5-µm transistors depletion-mode transistors were characterized. P-HEMT transistors with gate lengths of 0.1 and 0.15 µm were characterized.

B. Irradiation Conditions

Devices were irradiated at room temperature using the Indiana University Proton Cyclotron with high-energy protons at energies from 41 to 197 MeV, fluxes from 10^8 to $3x10^{11}$ protons/cm^2-s, and fluences from 10^{10} to $2x10^{14}$ protons/cm^2. The dose in rad(GaAs), D, is related to the fluence, Φ, through the relation,

$$D = 1.6x10^{-5} \cdot \Phi \cdot LET , \quad (1)$$

where LET is the linear energy transfer of the material and is given in units of MeV-cm^2/mg. At an energy of 100 MeV, the LET in GaAs is $4.7x10^{-3}$ MeV-cm^2/mg. Thus, at 100 MeV these fluxes and fluences correspond to dose rates from 7.52 rad(GaAs)/s to 22.6 krad(GaAs)/s and total doses from 752 rad(GaAs) to 15 Mrad(GaAs), respectively.

Proton energy was varied by placing copper blocks (thicknesses from 0 to 1.188 in.) in the beam line. This technique causes a spread in proton energy. The spread in proton energy and errors in calculating the peak energy (which become increasingly worse as the thickness of the copper block increases) set a practical lower-bound limit on the range of proton energies available for experimentation. For these experiments, we set the lower limit at 41 MeV. For a proton energy of 41 MeV, the spread in proton energy was calculated using a program called "straggle" to be 3.6 MeV (full width, half maximum).

C. Measurements

At the lower fluence levels, transistors and ICs were monitored for single-event effects. At the higher fluence levels, transistors and ICs were monitored for displacement damage.

Transistors were characterized for the radiation-induced degradation in threshold voltage, ΔV_{th}, pinch-off voltage, V_p, transconductance, g_m, and saturated drain current, I_{DSS}. The threshold voltage was determined from the voltage intercept of the square root of the drain current versus gate voltage curve, similar to that for MOS transistors. Large gate leakage currents for the 0.1-μm P-HEMT transistors prevented us from making threshold-voltage measurements for these transistors.

The saturated drain current was defined as the drain-to-source current at zero gate voltage. Pinch-off voltage was defined as the voltage corresponding to 1% of the saturated drain current. Transconductance was calculated from the equation

$$g_m = \left. \frac{\partial I_{DS}}{\partial V_{GS}} \right|_{V_{GS=0}} . \qquad (2)$$

Digital ICs were characterized for parametric degradation and functionality in situ using an HP82000 (50 MHz) tester. Single-event effects were characterized with a "one", "zero", and "checkerboard" pattern written to the memory.

MMIC circuits were characterized for proton-induced transient signals and displacement damage. Transient signals were monitored during irradiation using either a current-viewing transformer or a 200 Ω current-viewing resistor. To characterize displacement damage effects, the output levels of MMIC circuits were monitored. For these measurements RF power was supplied to the input of the MMIC circuit during irradiation and the output power was monitored by measuring the voltage across a pin diode connected to the output.

III. RESULTS AND DISCUSSION

A. Single-Event Upset

Protons cannot directly cause single-event upsets in most present-day GaAs or silicon circuits. For proton energies from 50 to 200 MeV, the linear-energy transfer (LET) for protons in GaAs varies from 3 to $8x10^{-3}$ MeV-cm^2/mg and is below that necessary to cause single-event upset. (For digital GaAs enhancement/depletion mode MESFET circuits, typical LET thresholds are ~0.5 to 2 MeV-cm^2/mg [4,5].) However, protons can induce upsets by dislodging atoms from their lattice sites or through nuclear interactions with lattice atoms. If the resulting secondary particles (e.g. alpha particles or displaced atoms) have higher stopping powers, i.e. LET, the secondary particles can cause sufficient ionization to induce single-event upsets.

Figure 1 is a plot of the SEU cross section for the E/D MESFET 14-bit counter versus proton energy. The data were taken with the counter written with either "ones", "zeros", or "checkerboard" pattern. For these experiments, the proton flux (~$5x10^8$ ions/cm^2-s) was adjusted to give approximately 100 errors in 100 to 300 s. The cross section increases slightly with proton energy as more charge is deposited per unit volume by secondary particles. The highest cross section measured was $2.1x10^{-9}$ cm^2 at a proton energy of 172 MeV with the counter written with a "zeros" pattern. Upsets were measured at the lowest proton energy examined (41 MeV).

Figure 2 is a plot of the SEU cross section for the HBT 128x16 register file versus proton energy. The data were taken with the register file written with either "ones", "zero", or "checkerboard" pattern. Similar to the results for the E/D MESFET counter, the cross section increases with proton energy. However, the maximum cross section measured for the register file was ~$1.7x10^{-10}$ cm^2 with the register file written in a "zeros" pattern and is approximately an order of magnitude lower than that measured for the counter.

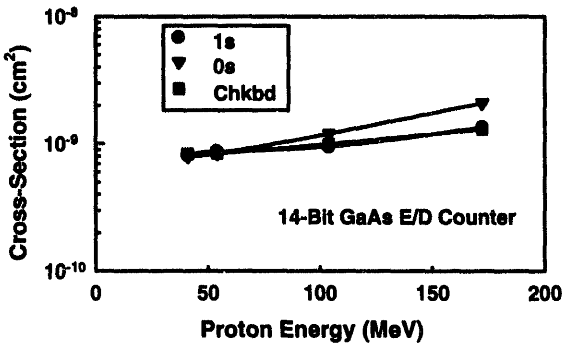

Figure 1: Upset cross section versus proton energy for a 1.0-μm E/D MESFET 14-bit counter irradiated with either a "one", "zero", or "checkerboard" pattern.

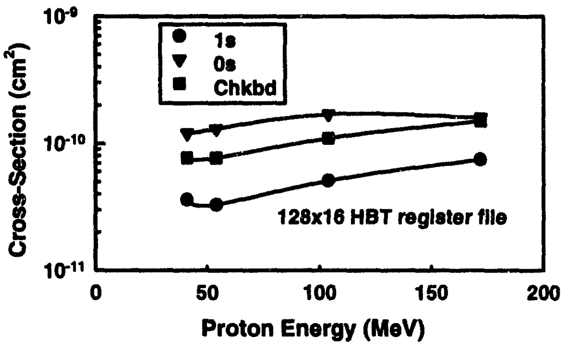

Figure 2: Upset cross section versus proton energy for a heterojunction bipolar transistor 128x16 register file irradiated with either a "one", "zero', or "checkerboard" pattern.

Note that the HBT register files show more of a pattern dependence than the GaAs MESFET counters.

Rough estimates of the soft errors rates for the counter and register file can be obtained using the one parameter Bendel model fitted at the highest energy [7]. (It is realized that better estimates for the soft error rates can be obtained using the two parameter Bendel model [8]. This model requires knowledge of the upset threshold for the devices. Unfortunately, we were unable to measure the upset threshold due to the lower limit (41 MeV) on the proton energy. However, soft error rates calculated using the one parameter Bendel model give a figure of merit for the sensitivity of these circuits to high-energy protons.) For a 1400 nmi circular orbit (near worst case for natural space environment), at 60 degree inclination, and with typical shielding, the proton-induced soft error rates are estimated [7] to be approximately $3x10^{-3}$ and 10^{-5} errors/bit-day for the counter and register file, respectively.

These proton soft error rates are comparable to those measured for these devices using heavy-ions. Figure 3 is a plot of the heavy-ion SEU cross section versus LET for the E/D MESFET 14-bit counter. The data were taken at Brookhaven National Laboratory's Tandem van de Graaff facility using heavy ions of Li-7, C-12, F-19, and Cl-35. The LET threshold was approximately 0.3 MeV-cm²/mg and the saturation cross section was $3.2x10^{-4}$ cm². Figure 4 is a plot of the heavy-ion SEU cross section versus LET for the HBT register file. The data were also taken at Brookhaven using heavy ions of C-12, F-19, Cl-35, Ni-35, and Br-79. The LET threshold was approximately 1.5 MeV-cm²/mg and the saturation cross section was $1.1x10^{-3}$ cm² for register files written with a "zero" pattern and $6.3x10^{-4}$ cm² for register files written with a "one" pattern. Assuming galactic cosmic rays, a geosynchronous orbit at 0 degree inclination, 200 mil aluminum shielding, and an Adams' 10% worst case environment, we expect a soft error rate of $6x10^{-4}$ errors/bit-day for the MESFET counters and a soft error rate of $8x10^{-6}$ errors/bit-day for the HBT register files written with a "zero" pattern.

The total soft error rate will include upset contributions from both protons and heavy ions. Thus, these results indicate that these types of memory-intensive digital GaAs MESFET and Al/Ga/As HBT ICs will be prone to both proton and heavy-ion induced upset in space.

In addition to the digital circuits, MMIC circuits were monitored for proton-induced I_{DD} transients at the device V_{DD} pin. Transistors taken from most of the MMIC circuits were also evaluated for drain current

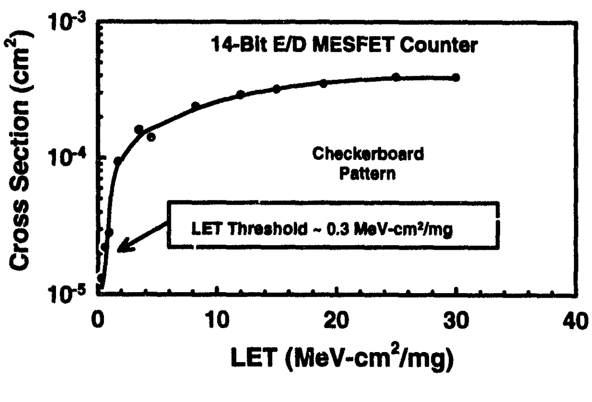

Figure 3: Heavy-ion upset cross section versus LET for 14-bit E/D MESFET Counters.

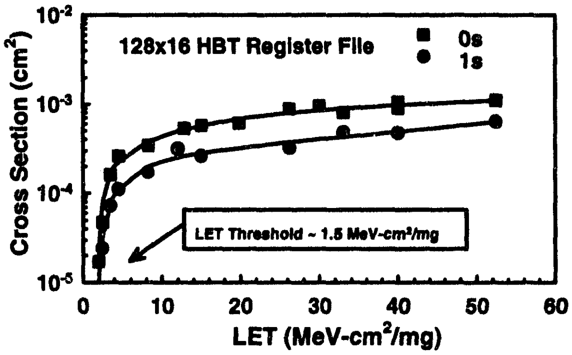

Figure 4: Heavy-ion upset cross section versus LET for 14-bit E/D MESFET Counters.

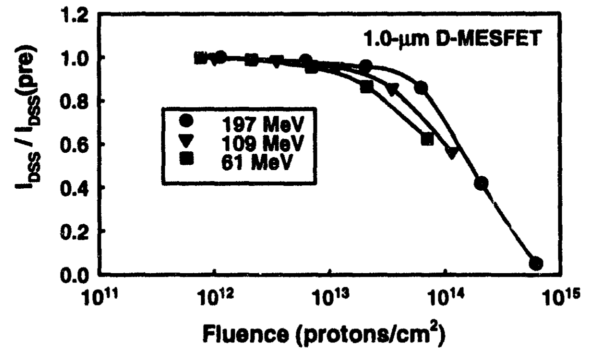

Figure 5: Normalized values for I_{DSS} versus irradiation for 1.0-µm depletion-mode transistors irradiated with 61 to 197 MeV protons.

transient signals during irradiation. Transient signals were detected from the transistors. The pulse width of the observed transient signals was less than 20 ns, close to the sensitivity of the instrumentation used for the measurements. No transient signals were detected on the MMICs. This may be due to the fact that each MMIC circuit had bypass capacitors on the device carrier which may have filtered out any transient signal.

B. Displacement Damage Effects

Another effect of proton irradiation on GaAs transistors is displacement damage resulting in a loss in carrier concentration and a decrease in carrier mobility. Devices were irradiated to determine the levels at which proton-induced displacement damage begins to affect device performance. In this section, we illustrate the effects of proton irradiation on these devices. Figure 5 is a plot of the source-to drain current, I_{DSS}, measured at zero gate voltage normalized to its preirradiation value versus proton fluence for 1.0-µm depletion-mode MESFET transistors. Proton energies of 61, 109, and 197 MeV were examined. The data indicate a small dependency on proton energy between 10^{13} and 10^{14} protons/cm^2 with the amount of degradation increasing with increasing proton energy. The transistors exhibit a 50% reduction in I_{DSS} at a fluence of approximately 10^{14} protons/cm^2. If I_{DSS} is plotted on a linear scale, I_{DSS} decreases linearly with fluence and follows the general relationship,

$$\frac{I_{DSS}}{I_{DSS}(pre)} = 1 - \alpha\varphi \,, \qquad (3)$$

where α is a proportionality constant and is equal to 2.04×10^{-15} cm^2/ion, and φ is the fluence. This type of relationship is often observed for degradation due to either proton- or neutron-induced displacement damage [9]. To verify that the degradation in I_{DSS} was due to displacement damage rather than ionization damage, devices were also irradiated to equivalent dose levels with a 10-keV x-ray source. No change in device parametrics were observed after irradiating to 10 Mrad(GaAs) for the x-ray exposures. Thus, the proton-induced degradation in I_{DSS} is most likely due to displacement damage.

Less proton-induced degradation was observed for shorter gate length (<1.0 µm) MESFET and P-HEMT transistors. Figure 6 is a comparison of I_{DSS} normalized to its preirradiation value as a function of dose for 0.5- and 1.0-µm depletion-mode MESFET transistors and 0.1- and 0.15-µm P-HEMT transistors. The proton energy was 61 MeV. Note that within measurement accuracy there is no degradation in I_{DSS} for the 0.1-µm P-HEMT transistors, even for fluences as high as 8.8×10^{13} protons/cm^2. However, as the channel length is increased, we observe an increase in the degradation of

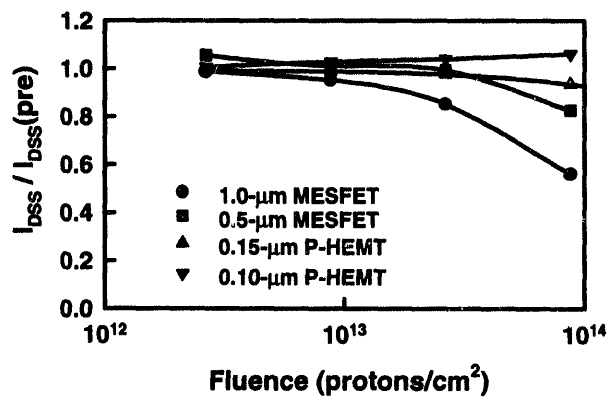

Figure 6: Normalized values for I_{DSS} versus irradiation for 0.5- and 1.0-µm depletion-mode MESFET transistors and 0.1- and 0.15-µm PHEMT transistors.

I_{DSS} for both MESFET and P-HEMT transistors. Similar trends were observed for the degradation in transconductance and change in pinch-off voltage with proton fluence. To the authors knowledge, this is the first time that a gate-length dependence has been shown for III-V components.

Similar results were obtained for the degradation in threshold voltage. Typical I-V curves for 1.0-µm depletion mode MESFET and 0.15-µm P-HEMT transistors are shown in Figs. 7a and 7b, respectively, preirradiation and after irradiating to a fluence of 8.8x10^{13} protons/cm^2. The transistors were irradiated with 61-MeV protons with a drain-to-source bias, V_{DS}, of 2 V. For the 1.0-µm MESFET transistors the threshold voltages were determined to be -0.70 V preirradiation and -0.54 V postirradiation. The large leakage current for the 0.15-µm P-HEMT transistors is caused by gate leakage. Analyzing the I-V curves in the upper region, the threshold voltages for the 0.15-µm P-HEMT transistors are -2.0 V preirradiation and -1.9 V postirradiation. For both transistors, the slope of the I-V curves changed slightly after irradiating to a fluence of 8.8x10^{13} protons/cm^2; 4.5% for the MESFET transistors and 3.8% for the P-HEMT transistors. The slope is related to the mobility of carriers in the channel region.

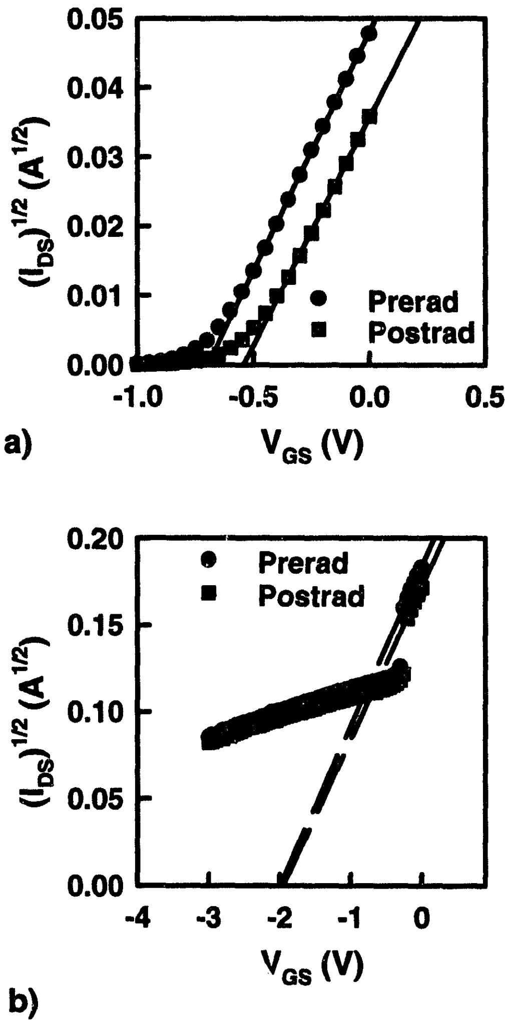

Figure 7: Gate voltage versus drain current I-V curves preirradiation and after irradiating to a fluence of 8.8x10^{13} protons/cm^2 with 61-MeV protons for a) a 1.0-µm depletion-mode MESFET and b) a 0.15-µm P-HEMT. For both transistors, measurements were taken and irradiations were performed with V_{DS} = 2 V.

Figure 8 is a plot of V_{th} normalized to its preirradiation value as a function of dose for 0.5- and 1.0-µm depletion-mode MESFET transistors and 0.15-µm P-HEMT transistors. Note that, as mentioned above, we were unable to determine the threshold voltage for the 0.1-µm P-HEMT transistors due to excessive gate leakage current. The preirradiation threshold voltages were 0.698, 2.40, and 1.99 V for the 1.0-µm MESFET, 0.5-µm MESFET, and 0.15-µm P-HEMT transistors, respectively. The decrease in V_{th} after irradiating to a fluence of 8.8x10^{13} protons/cm^2 for the 0.15-µm P-HEMT transistors was 0.05 mV (2.5%). The largest decrease in V_{th} was observed for the 1.0-µm depletion-mode MESFET transistors. After irradiating to a fluence of 8.8x10^{13} protons/cm^2, V_{th} decreased by approximately 160 mV (23%).

Whether the larger decreases in V_{th} and I_{DSS} with increasing channel length are due only to channel length

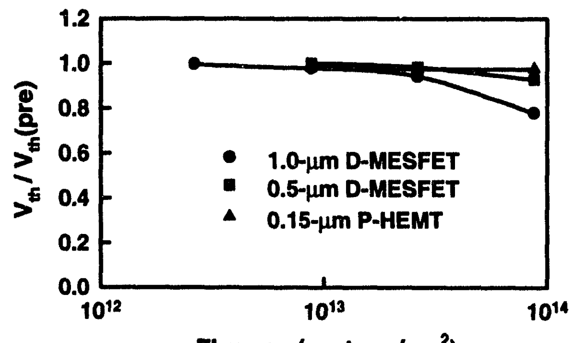

Figure 8: Normalized values for V_{th} versus irradiation for 0.5- and 1.0-µm depletion-mode MESFET transistors and 0.15-µm PHEMT transistors.

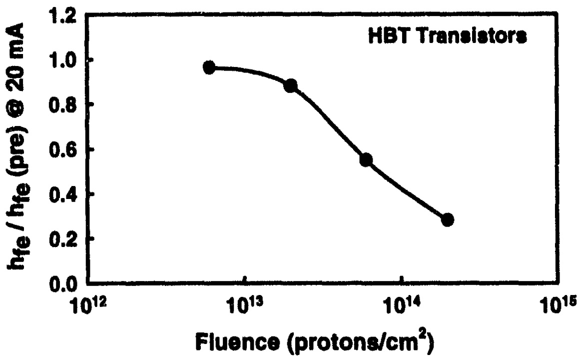

Figure 9: The degradation in h_{fe} for heterojunction bipolar transistors irradiated to a fluence of $2x10^{14}$ protons/cm^2 with 192-MeV protons.

differences or a combination of channel length differences and differences in structure between the MESFET and P-HEMT transistors is not known. It may be due to the reduced probability of damage clusters occurring for the short gate length transistors. However, additional work needs to be performed to identify the cause of the differences. These data indicate that the P-HEMT transistors with short channel lengths should be very robust to proton-induced damage for almost all applications.

Limited test data were obtained for the heterojunction bipolar transistors. HBT transistors were tested only at low current levels (test fixtures necessary to prevent oscillations at higher current levels were not available at the time of the tests). Figure 9 is a plot of h_{fe} measured at a collector current of 20 mA. The preirradiation values for h_{fe} varied from 13.3 to 8.6. Significant degradation in h_{fe} is observed at high fluences, decreasing to approximately 30% of its original value after irradiating to a fluence of $2x10^{14}$ protons/cm^2. Whether this same level of degradation would be observed under typical operating conditions is not known and needs to be determined in the future.

The output power levels of several MMIC circuits were also monitored during irradiation. For most of the circuits, the amount of degradation in output power was small for fluences as high as 10^{14} protons/cm^2. For instance, no change in output power level was detected after irradiating to a fluence of 10^{14} protons/cm^2 for the voltage-variable attenuator fabricated using 0.5-µm depletion-mode MESFET transistors. Some degradation in output power was observed for the frequency doubler fabricated using 0.25-µm depletion-mode transistors and for the amplifier fabricated using 0.5-µm depletion-mode MESFET transistors. After irradiating to a fluence of 10^{14} protons/cm^2, the output signal measured across a p-i-n diode dropped from 115 to 93 mV for the amplifier and from 31 to 27 mV for the frequency doubler. This drop in output signal corresponds to approximately a 1.8 and 1.2 dB loss in output power for the amplifier and frequency doubler, respectively. Thus, protons have little effect on the output power level of these MMIC circuits. We conclude, that, for a system fabricated using these advanced MMIC circuits, protons should have a negligible effect on system performance for practical proton irradiation levels and system requirements.

V. SUMMARY

In summary, a wide range of GaAs and other III-V device components were characterized in high-energy (40 to 200 MeV) proton environments for both displacement damage and single-event degradation. Consistent with previous results, memory-intensive GaAs MESFET and AlGaAs/GaAs HBT digital circuits were found to be sensitive to proton-induced single-event upset. Some degradation in transistor properties due to displacement damage effects were observed for 1.0-µm MESFETs after irradiating to a fluence of ~10^{14} protons/cm^2. However, MMIC circuits fabricated using advanced processes were found to be relatively insensitive to proton-induced single-event upset or displacement damage. 0.1-µm P-HEMT transistors showed no degradation in performance after irradiating to a fluence of ~10^{14} protons/cm^2 with protons at energies from 61 to 197 MeV.

Acknowledgments

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