Testing Radiation damage in III-V Transistors

R.Anholt[!], J. Gillespie[$], R. Dettmer[$], J.Sewell[$], C.Bozada[$], R. Bhattacharya[#], H. Evans[#]

[!]Gateway Modeling, Inc., Minneapolis, MN 55414, tel:612-339-4239, anholt19@idt.net
[$]Air Force Research Laboratory, Wright Patterson AFB, Ohio, 45433
[#]Universal Energy Systems, Dayton Ohio 45432

ABSTRACT

HBTs, MESFETs, and pHEMTs were measured on-wafer before and after irradiation by 3MeV protons at a dose of 10^{13} cm^{-2}. The HBT current gains decreased because the collector currents decreased and the base currents increased. This was modeled using G-PISCES-2B assuming that the radiation reduced the recombination lifetimes in the base by about a factor of 0.05. The model is partially verified by periphery-to-area dependencies. The FET and HEMT pinchoff voltages V_p increased by 6 to 19% of the depletion voltage (V_{bi}-V_p, where V_{bi}~0.78V) and are modeled assuming 0.6 to $1.2x10^{16}cm^{-3}$ deep-donor and acceptor impurities are created by the irradiation. This work shows the value of proton implantors in assessing radiation damage to space-based electronics.

INTRODUCTION

In certain orbits, electronics in space may be exposed to as many as 10^{11} protons/cm^2 per day with energies exceeding 1MeV. Protons can cause two kinds of damage: displacement damage where Ga and As atoms are knocked off their sites to become traps, and ionization energy which is electron-hole pair formation. In CMOS transistors the holes can become trapped in oxides leading to threshold voltage shifts. The traps reduce recombination lifetimes and compensate shallow impurities. When we compare the amount of energy in Rads that 10^{13} cm^{-2} 1MeV particles can deposit (Table 1), protons are clearly the most important thing to worry about in space.

Table 1:Energy deposition in Rads for $10^{13}cm^{-2}$ 1-MeV particles

Particle	Displacement	Ionization
Gamma rays	0	6000
Electrons	0	$2x10^5$
Neutrons	0.004	0
Protons	16000	$16x10^6$

EXPERIMENT

Proton implantors are an ideal way to test radiation hardness. They produce a uniform dose over a large-diameter, so that whole wafers with process control monitors and different device sizes can be exposed and tested on-wafer. In the present experiment we exposed stripes of a single InGaP/GaAs HBT wafer to doses of 10^{10} to 10^{13} 3-MeV protons/cm^2 (where about 1MeV was lost in our 15µm-thick thermal shunts [1]). On this wafer we had HBTs with dot or bar-type emitters with diameters or widths from 2 to 14µm, but with the same total emitter area, enabling us to investigate periphery to area effects. Only the dose of $10^{13}cm^{-2}$ gave measurable effects.

In a second experiment, we irradiated reticles from several in-house HBT wafers as well as FET and HEMT reticles from commercial foundries, which were mounted on a 4-inch Si wafer and were tested on-wafer before and after irradiation by $10^{13}cm^{-2}$ 3-MeV protons.

HBT RESULTS

Figure 1 shows forward Gummel IV curves before and after irradiation by 10^{13} protons/cm^2. The main effect is that the current gains decrease from about 6 to less than 2 at V_{be}=1.25V, and the emitter resistance appears to increase. The collector ideality factor was invariant, but the base factor increased from 1.1 to 1.2. The emitter resistance increase is not seen in the transmission-line-method resistance monitors that were exposed to the same radiation. They gave nearly equal contact and sheet resistances before and after irradiation[1]. The apparent emitter-resistance increase is due to the current gain reduction: Normally $|I_e|R_e+I_bR_b$ is approximately equal to

[1] Proton isolation implants are done with at least ten times higher doses, but where the peak of the damage profile is closer to the active region. Our peak is way below the active region, so we are producing far less damage in the active area than isolation implants.

I_cR_e where R_e is the contact resistance divided by the fixed emitter area. However, when the current gain is approximately 1, R_b makes a sizable contribution to the apparent resistance. For dot-emitters, R_b per dot is approximately constant, but for the small emitters we use 10 to 20 dots, so R_b is 10 to 20 times smaller than for large-diameter HBTs with a single dot. Thus in Fig.3 the increase in the post-irradiated emitter resistance with diameter is due to the R_b increase[1].

The primary reason to investigate periphery to area (P/A) effects is that in Si bipolar transistors, researchers have seen effects of hole trapping in oxide layers which affects base currents. (By analogy we worry about the polyimide layers under our shunts.) Figure 2 shows the ratio of base currents at V_{be}=1.25V. Before irradiation, we can write the base currents as $I_b=I_{bulk}+I_{surf}P/A$, where I_{bulk} and I_{surf} are empirically determined. From this we can hypothesize that the damage ratio after irradiation can by written as $(I_{bulk}D+I_{surf}D_pP/A)/I_b$ where D and D_p are damage ratios for the bulk and surface currents. In Fig.2 we have models for different values of D_p and D. Clearly bulk damage is the main effect; the error bars are consistent with almost no damage to the surface currents (D_p~0).

Figure 4 shows G-PISCES-2B models of damaged and undamaged Gummel curves. The model uses a recombination lifetime of 10ps in the base, which is about a factor of 0.05 below the undamaged lifetime. This result is consistent with measurements of lifetimes of irradiated GaAs layers with doping concentrations of $2x10^{15}cm^{-3}$[2]. They found that for 0.5 to 1.5-MeV protons the lifetimes decreased to 10 to 100psec. This is due mainly to displacement damage. Comparing Rads in Table I, our proton dose is equivalent to a γ-ray dose of $2.7x10^{16}cm^{-2}$, which according to [2] gives a lifetime of 37nsec, which adds negligibly to the un-irradiated lifetime.

Normally one would think that decreasing the base lifetime would just increase the base current, but at these lifetimes, a significant fraction of the electron current J_n transiting the base is recombined with holes, leading to smaller collector currents (Fig.5).

Some of the damage is annealed out in HBTs under normal operation over a period of a few hours. Under no operation, the damage remains, but operating at $\sim10^5W/cm^2$, the current gains increase to about 3 very quickly then change more slowly. Up to ~100 hours, the collector currents do not recover the original current gains (Fig.6).

Our second experiment compared HBTs fabricated from wafers from different epi vendors. A dependence on the base thickness is expected because the bulk recombination increases linearly with the base thickness. For the same layouts, we can write $I_b=I_{surf}+I_{bulk}DW_b/W_{bo}$, where W_{bo} is some nominal base thickness, D is the damage ratio, and I_{surf} and I_{bulk} are independent of base thickness. Figure 7 shows results and the PISCES model for several wafers. No strong dependence is observed, which in part is due to current gain variations that come from processing and materials, which makes I_{surf}/I_{bulk} vary randomly. From this one cannot conclude that any HBT material is better than any other. At best if one can make HBTs where surface recombination dominates, they would be more radiation hard.

MESFET AND HEMT RESULTS

Figure 8 shows transfer curves for a $0.6x100\mu m^2$ MESFET and a $0.2x100\mu m^2$ pHEMT before and after irradiation. Here the major effect is a shift in the pinchoff voltage, which is also observed in gamma-ray irradiation with $>10^8$Rads [7]. We modeled this with PISCES assuming that 1.2 or $0.6x10^{16}cm^{-3}$ deep donors and acceptors are created throughout the damaged region in the irradiation. Calculations with the TRIM Monte-Carlo program[3], give $\sim2x10^{16}cm^{-3}$ vacancy creation in the top 1μm of GaAs after penetrating ~1μm of gold gate material. It is likely that both deep donors and deep acceptors are created, but the deep acceptors compensate the implanted donors (the deep donors are neutral)[4]. The gate current I_g-V_g curves are identical before and after irradiation, indicating that the Schottky gate is not affected by the radiation.

In comparing MESFETs and HEMTs from different vendors, comparing changes in I_{dss}, g_m, or gains is not meaningful, because the major effect is just a shift in the IV curves. The pinchoff-voltage V_p change depends on the shape of the profile [5], but some comparative information can be obtained by comparing the change in the depletion voltage, defined as V_{bi}-V_p, where V_{bi} is the Schottky voltage.

Table 2 compares the change in depletion voltages and I_{dss} for 10^{13} protons/cm^{-2}. The first two MESFETs were recessed etched and ion-implanted (II), with gate lengths around 0.5μm. The next two were flat, self-aligned (SA), ion-implanted MESFETs with smaller gate lengths. The last two are GaAs pHEMTs with gate lengths around 0.2μm. Two of the MESFETs were available in horizontal and vertical layouts with different pinchoff voltages due to the piezoelectric effect or etching chemistry.

The changes in the pHEMT depletion voltages were consistently smaller than in the MESFETs. This is in part due to the narrower electron profiles, but PISCES simulations also required a smaller trap concentration

(0.6 versus $1.2x10^{16}cm^{-3}$) to match the results. One self-aligned MESFET pinchoff voltage decreased. The PISCES simulations of this device also predicted the pinchoff voltage should increase, similar to Fig.8. The device had a very high buried-p-layer concentration and significant piezoelectric effects. Whether the piezoelectric stress also changed during the irradiation we could not determine.

CONCLUSIONS

In conclusion this paper demonstrates the value of proton implantors to assess radiation hardness to particles of importance in space applications, and presents a survey of damage effects and modeling of the damage. The only limitation is that protons create both displacement and ionization damage, and it is not possible to determine which is the most effective. Other γ-ray irradiations have seen almost no effects on HBTs[6], MESFETs and pHEMTs[7], and laser lifetimes[2] for over ten times more ionization Rads than in our proton measurements, so we infer that we are mainly observing the effects of displacement energy deposition.

REFERENCES

1. R.Anholt et.al. Sol.State Elect., vol.41, p.1739-1743, 1997
2. M.Parenteau, C.Carlone, D.Morris, S.M.Khanna, IEEE Trans. Nucl.Sci. vol.44, p.1849-1855, 1997
3. J.F.Ziegler, J.P.Biersack, U.Littmark, Stopping and Range of ions in solids (Pergamon, Elmsford, N.Y. 1985).
4. R. Anolt and T.Sigmon, J.Elect. Mat., vol.17, p.5-10, 1987
5. C.H.Chen, M.Shur, A.Peczalski, IEEE Trans Elect. Dev. vol.33, p.792-797, 1986
6. Y.Song, M.E.Kim, A.K.Oki, M.E.Hafizi, J.B.Camou, K.W.Kobayashi, 1989 IEEE GaAs IC Symp.p.155-158
7. K.Matsuzaki et.al. 1997 Fourth European Conference on Radiation and Its Effects on Components and Systems Proceedings (RADECS 97).

Table 2. Changes in MESFET and HEMT depletion voltages and I_{dss}

Device	V_p (V)	$\delta V_p/V_{dep}$	$\delta I_{dss}/I_{dss}$
Etch/II 1	-1.85	0.19	-0.32
Etch/II 2H	-0.8	0.14	-0.30
Etch/II 2V	-0.9	0.13	-0.24
SA/II 1H	-0.37	-0.11	0.06
SA/II 1V	-0.77	-0.03	-0.17
SA/II 2	-1.7	0.13	-0.18
pHEMT 1	-0.5	0.055	-0.14
pHEMT 2	-0.82	0.063	-0.12

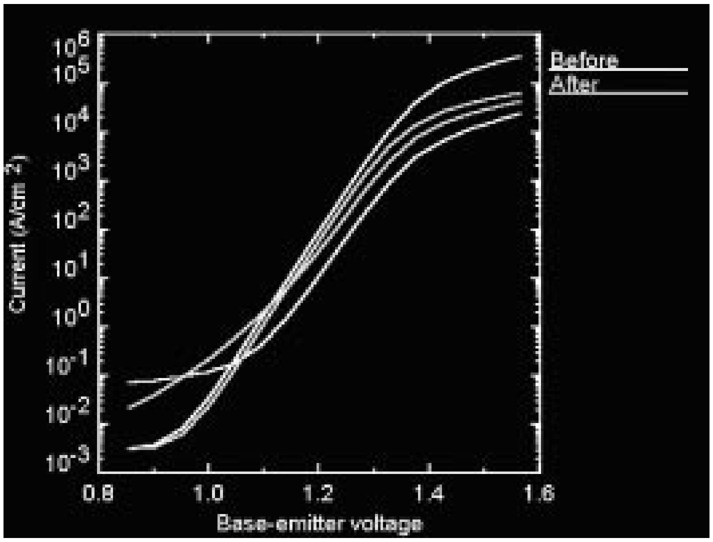

Fig.1. Forward Gummel collector and base current curves before and after irradiation. For a color picture click here.

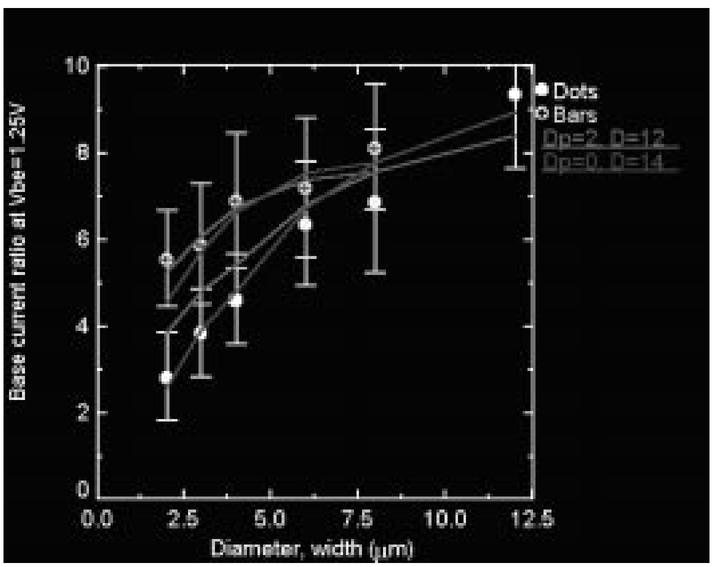

Fig.2. Ratios of damaged to undamaged base currents at V_{be}=1.25V. For a color picture click here.

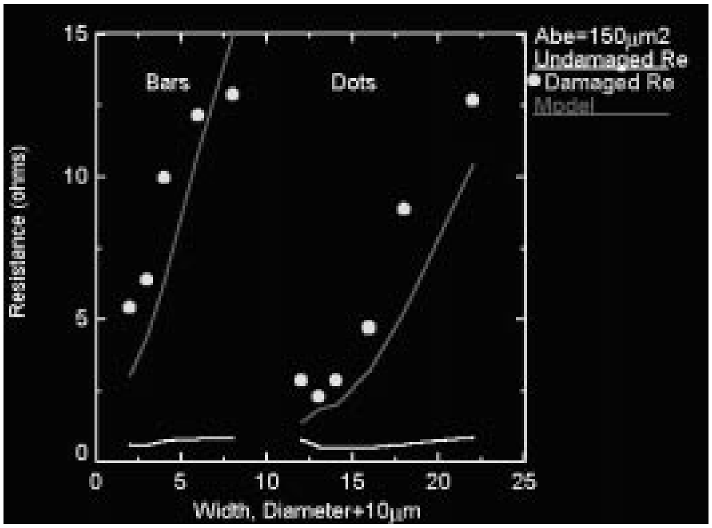

Fig.3. Extracted emitter resistance before and after irradiation and a model. For a color picture click here.

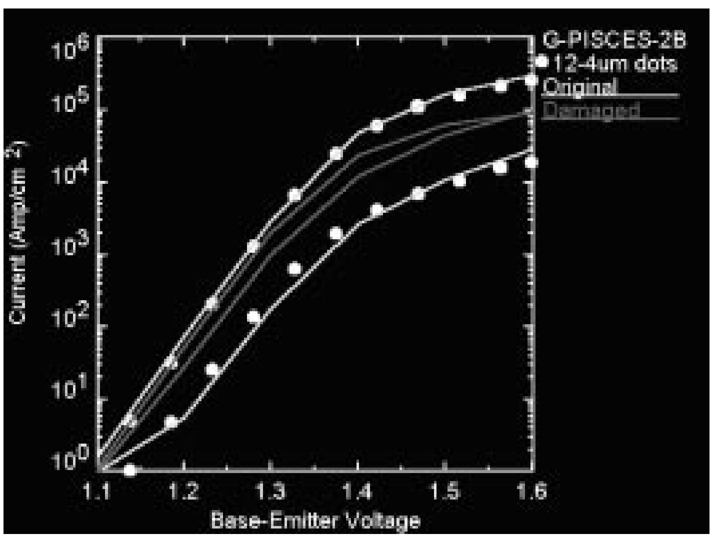

Fig.4.PISCES simulations of forward-Gummel base and collector currents before and after irradiation. For a color picture click here.

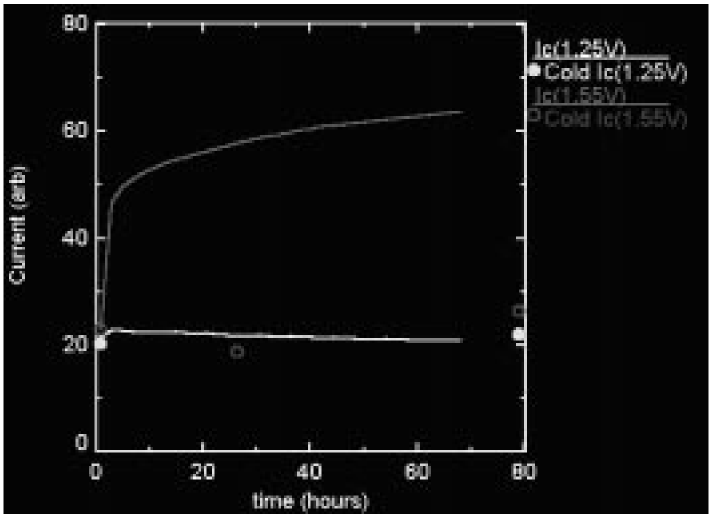

Fig.5. Collector current densities mid-emitter and recombination rates (A/cm^3). For a color picture, click here

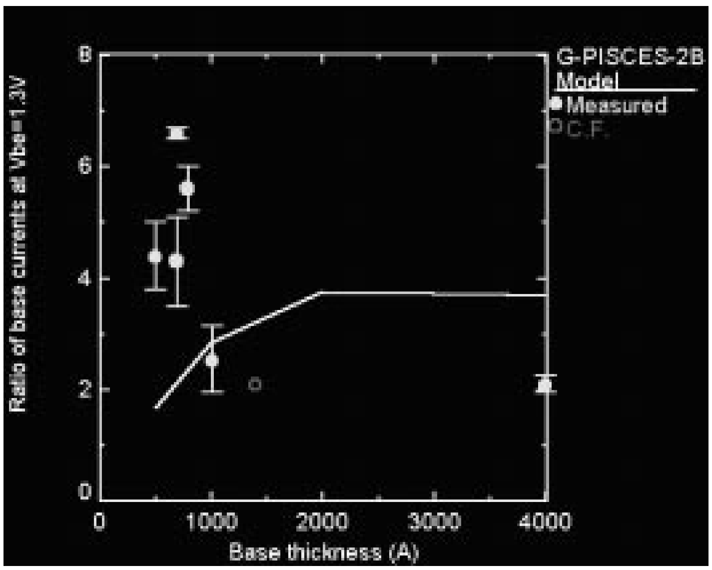

Fig.6. Change in the base and collector currents after irradiation for HBTs operating at 10^5W/cm^2 or off (Cold). For a color picture, click here

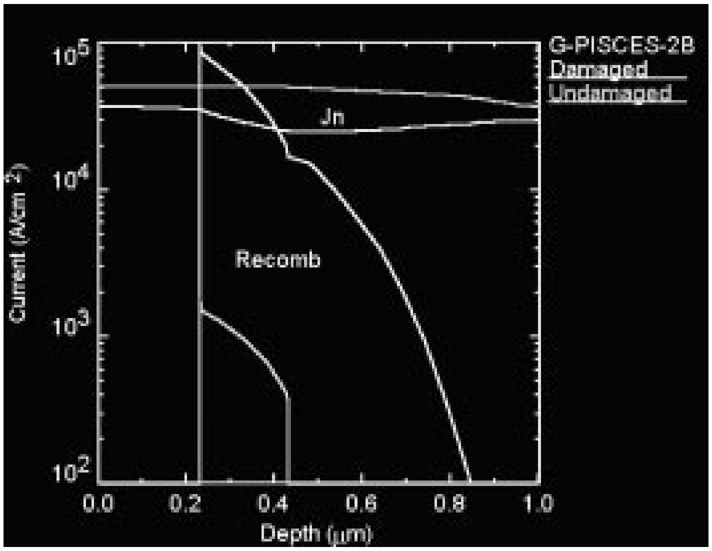

Fig.7.Ratio of base currents at V_{be}=1.3V after to before irradiation for wafers with different base thicknesses. All have thermal shunts and 12 4μm dots except that from a commercial foundry (CF) For a color picture, click here

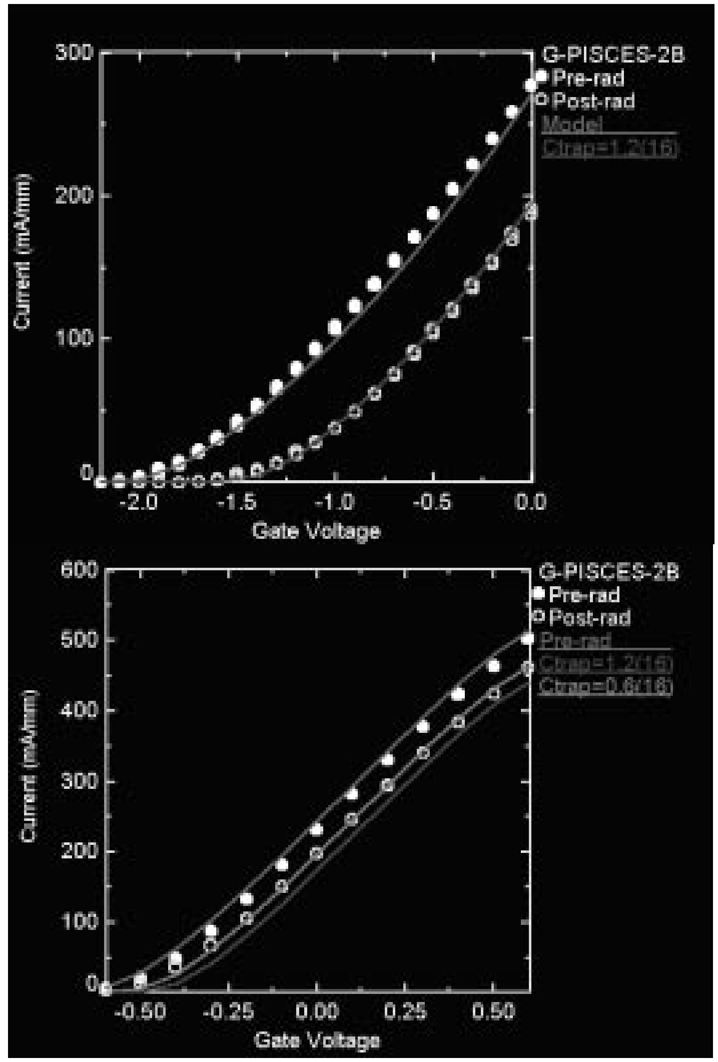

Fig.8. MESFET and pHEMT transfer curves at V_{ds}=2Vbefore and after irradiation compared to PISCES model with different deep trap concentrations.