W. T. Anderson, Jr.* and S. C. Binari*

ABSTRACT

Transient radiation effects following 20-60 ns electron pulses were measured in GaAs FETs and ICs operating at X-band. Long-term transients in RF output power and drain current were observed in all devices and ICs except FETs fabricated with a buried p-layer. Only the prompt (20 ns) photocurrent response was observed in FETs with a buried p-layer. The long-term transients are explained by a model of substrate trapping and backgating.

INTRODUCTION

Long-term transient changes in the drain current, I_{DS} , of commercially available GaAs FETs induced by pulsed ionizing radiation were first reported in 1979 [1], and upset in IC's resulting from pulsed ionizing radiation was reported [2] at the same time. Integrated circuits of MSI complexity have also been investigated [3] using 20 ns flash x-ray (FXR) pulses. These digital ICs were fabricated on Cr-doped substrates by direct ion implantation and showed a logic upset threshold of 1×10^8 rad(GaAs)/s, with functional operation restored in 5 μ s after exposure to 2×10^{10} rad(GaAs)/s. Since then, attempts have been made to reduce the long-term radiation transients, e.g., by using undoped substrates [4]. However, use of undoped substrates was found to reduce the change in I_{DS} by only about a factor of two. Much larger reductions in long-term transients were reported [5] in another study using a different method to grow the undoped substrates, so that use of very pure undoped substrates is a useful method to reduce the amplitude of the radiation transients. The use of these undoped substrates in the all implanted enhancement mode JFET technology has resulted in the most radiation tolerant ICs to date. Logic upset was reported at dose rates in the range $5-10 \times 10^{10}$ rad(GaAs)/s [5].

Considerable progress in the radiation hardening of GaAs devices has been made recently by a fabrication method developed at NRL in which a buried p-layer is placed below the active n-layer [6]. Reductions in the change in I_{DS} of up to two orders of magnitude were measured in FETs fabricated in Cr-doped substrates with the buried p-layer compared to FETs with only an n-implanted channel following a 100 rad FXR pulse. The results of this study further confirmed that the transient radiation response in ion-implanted GaAs FETs is due to electron and hole trapping in the substrate [4,6].

Almost all of the previous studies of discrete GaAs FETs and analog ICs have been made with the devices under DC conditions with measurements made of the change in I_{DS} . In the present paper, radiation effects measurements are extended to actual operating conditions at X-band of GaAs FETs and monolithic analog ICs. The purpose of the work reported here was to evaluate the radiation hardness of GaAs FETs and ICs under high frequency operating conditions. Measurements were made of the gain at X-band and I_{DS} following 60 ns, 40 MeV electron pulses using the NRL Linac at radiation levels up to 5 Krad(GaAs) and dose rates of 9×10^{10} rad-(GaAs)/s. Measurements of I_{DS} transients were also made using the 20 ns electron pulse beam at the White Sands Missile Range Linac.

EXPERIMENTS

FETs and IC

Two types of commercially available low noise GaAs FETs (with nominally 1 μ m gate lengths), two types of relaxed geometry GaAs FETs (with and without a buried p-layer), and a GaAs monolithic amplifier were studied. These devices are described in Table I. Devices fabricated on both Cr-doped and undoped substrates were investigated. Passive elements on the monolithic amplifier chip consisted of interdigitated capacitors and short microstrip inductors. Fabrication of the NRL FETs, with and without a buried p-layer, has been described elsewhere [6].

Table I. GaAs FETs and integrated circuit studied for transient radiation effects.

TYPE	GATE METAL	L_g (μ m)	W_g (μ m)	ACTIVE LAYER/SUBSTRATE
A	Al	0.8	300	IMPLANTED/UNDOPED
C	TIW	1.1	360	IMPLANTED/Cr-DOPED
NRL	Cr/Au	8.0	250	IMPLANTED/Cr-UNDOPED
MONOLITHIC AMPLIFIER	Ti/Pt/Au	1.0	900/2400*	IMPLANTED/UNDOPED

L_g = GATE LENGTH
 W_g = GATE WIDTH

*1ST STAGE/2ND STAGE

Linac and Experimental Conditions

A diagram of the experimental setup used to make measurements at X-band is shown in Fig. 1. 60 ns pulses of 40 MeV electrons were provided by the NRL

Fig. 1. Diagram of experimental setup used to make transient radiation effect measurements on FETs and ICs at X-band.

Linac without the presence of any appreciable tail or dark current. Measurement of the radiation dose of each pulse was made using a thermoluminescent device (TLD). In order to keep the cables short, it was found

*Naval Research Laboratory, Washington, D.C. 20375

necessary to place all the high frequency equipment in the radiation testing room. Only the current probe, current probe amplifier, DC power supplies, and oscilloscope were placed in a nearby room and connected to the test circuit by low-loss coaxial cables about 100 ft in length. Separate tests in which the beam was deflected just before entering the testing room showed that electromagnetic pickup by the cables had negligible effects on the measurements. For individual FETs, the devices were placed under bias and then final tuned for maximum output power in the testing room using twinsleeve tuners. Monolithic amplifiers had the necessary tuning elements on-chip and no further tuning was required; in this case, the twinsleeve tuners were removed. Output power was measured with a crystal detector and I_{DS} with a current probe. The gain was calculated from P_O after calibration of the crystal detector at the measurement frequency. All devices and ICs exhibited gain except the NRL relaxed geometry FETs, which did not have gate lengths short enough to result in gain at 10 GHz. Transient responses of P_O and I_{DS} were recorded on film down to $1\mu s$ using a dual trace oscilloscope.

Experimental Results

Figure 2 shows the transient response at 10 GHz of a type C device on four different time scales from $2\mu s$ to $1s$. The power fell to zero in about $1\mu s$ while I_{DS} exhibited large oscillations which damped out in $5\mu s$.

Fig. 2. Transient radiation response of output power (P_O) at 10 GHz and drain current (I_{DS}) of a type C GaAs FET following a 60 ns pulse of 40 MeV electrons (3.5 krad , $5.8 \times 10^{10} \text{ rad/s}$).

These oscillations in drain current are attributed to the long cable length of the bias leads. After about $5\mu s$, P_O tracked I_{DS} in the sense that the P_O values corresponded to I_{DS} values when I_{DS} was changed by varying the gate bias. This was verified by a separate set of measurements while the device was in the same experimental setup with the same tuning. Three recovery times were observed (7 ms, 20 ms, and 3s) which correspond to three different trapping levels in the substrate [6]. The recovery time is defined as the time measured on the oscilloscope traces for I_{DS} or P_O to return to within 10% of the steady state value. Measured in this way, the values are accurate to about $\pm 20\%$.

Similar results were observed with type A FETs as shown in Figure 3. In this case, the recovery times

Fig. 3. Transient radiation response of output power (P_O) at 10 GHz and drain current (I_{DS}) of a type A GaAs FET following a 60 ns pulse of 40 MeV electrons (3.0 krad , $5.0 \times 10^{10} \text{ rad/s}$).

were 22 μs , 3 ms, and 300 ms. The longest recovery time is shown more clearly in Fig. 4 which shows the radiation response of two different type A FETs under large gate bias ($-1.2V$ in the left photographs) and under more normal bias conditions ($-0.8V$ in the right photographs). These data demonstrate the bias dependent

Fig. 4. Transient radiation response of output power (P_O) at 10 GHz and drain current (I_{DS}) of type A GaAs FETs following a 60 ns pulse of 40 MeV electrons.

behavior of GaAs FETs following irradiation at large dose rates. The percent change of I_{DS} and P_O is largest when the device is operating at low power near pinchoff. With the gate bias near pinchoff ($V_G = -1.2V$) the drain current and output power dropped nearly to zero following the radiation pulse. Typically, the total change in I_{DS} or P_O is the same regardless of the bias conditions. These data show only the long-term transient behavior of the devices because data recordings with the oscilloscope could only be obtained down to the $2\mu s$ scale. The actual prompt response due to the photocurrent is a large increase in I_{DS} which occurs in less than 1 ns and is larger than the long-term transient by a factor of

about 10, as will be discussed below.

Also shown in the bottom right photograph of Figure 4 is the trace obtained when the electron pulse is deflected just before entering the radiation testing room and represents the electromagnetic pickup of the device and circuit. There is a small amount of pickup immediately following the electron pulse which has a period of about 1 μ s. This, however, is much smaller than the 0.2 μ s oscillations shown in Figs. 2 and 3, which appear to be ringing of the bias circuit following the very large initial increase in I_{DS} (prompt response).

The radiation responses of the relaxed geometry FETs fabricated [6] at NRL, with and without the implanted buried p-layer, are shown in Figure 5. A large transient response was observed in the devices with only the Si implanted active layer, as shown for a typical device in the left photograph. The output power decreased following the pulse and recovered with the same behavior as I_{DS} , with time constants of 10–20 μ s, $\sim$ 5 ms, and $\sim$ 60 s, as previously reported [6]. Only the devices with the buried p-layer showed no

attempt to understand the total circuit response. Large current changes were observed across one of the interdigitated capacitors when irradiated while biased up to 15V. For example, at 15V bias, a current flow of 35 mA was observed immediately after the radiation pulse with almost complete recovery after about 10 μ s. The capacitor current also exhibited a longer-term transient of about 1 ms, indicating substrate trapping resulted in a change in voltage across the capacitor.

Prompt Response

Measurements of the prompt photocurrent response in I_{DS} were made at the White Sands Missile Range Linac. Typical electron pulse widths were 20 ns, as measured with a Si PIN diode, and the change in I_{DS} , with the device DC biased, was recorded using a digitizer with the FET in the same microwave mount used for the measurements at 10 GHz. The results shown in Fig. 7 for FET types A and C represent the change in I_{DS} as a voltage drop across a 50 Ω resistor in the digitizer. In the figure, a negative voltage represents a positive current change in the device. The trace from 100 to 350 ns almost exactly match the electron pulse trace

Fig. 5. Transient radiation response of output power (P_o) at 10 GHz and drain current (I_{DS}) of GaAs FETs fabricated at NRL on the same substrate, following a 60 ns pulse of 40 MeV electrons (1.5 Krad, 2.4×10^{10} rad/s, on the left; 1.1 Krad, 2.0×10^{10} rad/s, on the right). Bias conditions: $V_D = 4.00V$, $V_G = -1.12V$ on the left; $V_D = 3.99V$, $V_G = -1.80V$ on the right.

A number of monolithic amplifiers of different types were studied and the transient response following irradiation was different depending on the circuit elements on the chip. Figure 6 shows the transient response of one of these monolithic amplifiers while operating close to the 1 dB gain compression point at 6 GHz. Radiation responses in other amplifiers will be reported at a later date. The response was different from that of individual FETs in that the oscillations in I_{DS} on the 2 μ s scale were much longer and P_o fell to zero in less than 2 μ s without following I_{DS} . After this initial response, the transient behavior was similar to the FETs, with recovery times of 100 μ s and 100 ms. The source of the 8 μ s period oscillations in I_{DS} , which is the total current in both FET stages, is evidently the circuit response on the chip to changes in the interdigitated capacitors and inductors induced by the radiation pulse. Ringing of the external circuit, as with the individual FETs, is seen weakly in the P_o trace on the 2 μ s scale. The behavior of individual circuit elements following the radiation pulse should be studied, where the external terminals allow, in an

indicating the change in I_{DS} is due primarily to unrecombined photo-electrons and holes in the active layer and substrate. A long tail from 120 ns out to 350 ns on the traces is due to a similar tail on the electron pulse, including the small change between 300 and 350 ns. Note that the long-term transients, shown in the traces on the right, are smaller than the photocurrent changes by about an order of magnitude and are negative. These long-term transients are essentially the same as measured in these devices when operated at 10 GHz.

Figure 8 shows the prompt response and long-term transients in the NRL devices with and without a buried p-layer. The prompt response is similar to that in Fig. 7. Note that the buried p-layer has the effect of reducing the photocurrent by a factor of two compared with the device with only a Si implanted active layer. Since these devices were fabricated side-by-side on the same wafer, this indicates that there may be a component to the photocurrent in the single implanted device which has its origin in the semi-insulating substrate.

Fig. 6. Transient radiation response of output power (P_O) at 6.0 GHz and drain current (I_{DS}) of a monolithic GaAs amplifier following a 60 ns pulse of 40 MeV electrons.

Fig. 7. Transient radiation response of type A and C GaAs FETs, expressed as a change in I_{DS} measured as a voltage change V across 50Ω .

The conducting p-layer in the double implanted device may act to shield the active channel from this contribution to the photocurrent. Note also that no long-term transient was observed in the FET with a buried p-layer at a dose rate of $1.27 \times 10^{10} \text{ rad(Si)/s}$.

CONCLUSIONS

The GaAs FETs and monolithic ICs which were studied showed loss of output power following ionizing irradiation by electron pulses at dose rates of $1-9 \times 10^{10} \text{ rad/s}$. This power loss was observed as a long term transient, in which case the loss of output power corresponded to the long term transient in the drain current, and as an 1-10 μ s upset following the irradiating pulse. It appears that this upset is the result of ringing of the external circuit, or a combination of the external and internal circuits in the case of monolithic amplifiers, caused by the large 20-60 ns photo-

Fig. 8. Transient Radiation response of NRL GaAs FETs, expressed as a change in I_{DS} measured as a voltage change V across 50Ω .

current induced by the irradiating pulse. These effects are most pronounced at low current levels and will thus be important for low power operation in applications such as communication satellites.

The only devices in which long-term transients were not observed in either drain current or output power were FETs fabricated with a buried p-layer. All long-term transient effects appear to be consistent with earlier work [4,6] in which the effects were explained by a model of substrate trapping and backgating.

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