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, IDSS, 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 1x10^8 rad(GaAs)/s, with functional operation restored in 5 μs after exposure to 2x10^10 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 Idss 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 5-10x10^10 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 Idss of up to two orders of magnitude were measured in FETs fabricated on 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 Idss. 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 Idss following 60 ns, 40 MeV electron pulses using the NRL Linac at radiation levels up to 5 Krad(GaAs) and dose rates of 9x10^10 rad (GaAs)/s. Measurements of Idss transients were also made using the 20 ns electron pulse beam at the White Sands Missile Range Linac.

FETs and ICs

Two types of commercially available low noise GaAs FETs (with nominally 1 μm gate length), 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.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>GATE METAL</th>
<th>Lg (μm)</th>
<th>Wg (μm)</th>
<th>ACTIVE LAYER/SUBSTRATE</th>
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<tbody>
<tr>
<td>A</td>
<td>Al</td>
<td>0.8</td>
<td>300</td>
<td>Implanted/Undoped</td>
</tr>
<tr>
<td>C</td>
<td>TiW</td>
<td>1.1</td>
<td>360</td>
<td>Implanted/Cr-Doped</td>
</tr>
<tr>
<td>NRL</td>
<td>Cr/Au</td>
<td>8.0</td>
<td>250</td>
<td>Implanted/Cr-Undoped</td>
</tr>
<tr>
<td>MONOLITHIC</td>
<td>Ti/Pl/Au</td>
<td>1.0</td>
<td>900/2400*</td>
<td>Implanted/Undoped</td>
</tr>
<tr>
<td>AMPLIFIER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ L_g = GATE LENGTH \]
\[ W_g = GATE WIDTH \]

*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...
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 twissleeve tuners. Monolithic amplifiers had the necessary tuning elements on-chip and no further tuning was required; in this case, the twissleeve 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 1$\mu$s. The power fell to zero in about 1$\mu$s while $I_{DS}$ exhibited large oscillations which damped out in 5$\mu$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 3$\mu$s) 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 ±20%.

Similar results were observed with type A FETs as shown in Figure 3. In this case, the recovery times were 22$\mu$s, 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 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 10%.
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 µs. This, however, is much smaller than the 0.2µs oscillations shown in Figs. 2 and 3, which appear to be ringing of the bias circuit following the very large initial increase in Idg (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 Idg, with time constants of 10-20 µs, ~ 5 ms, and ~ 60 s, as previously reported [6]. Only the devices with the buried p-layer showed no measurable changes in P0 or Idg. An attempt to understand the total circuit response. Large current changes were observed across one of the interdigitated capacitors when irradiated while biased up to 15 V. For example, at 15 V bias, a current flow of 35 mA was observed immediately after the radiation pulse with almost complete recovery after about 10 µs. 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 Idg 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 Idg, 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 Idg 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 indicating the change in Idg is due primarily to uncombined 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.

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 $1.27\times10^{10}$ 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 $1-9\times10^{10}$ 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 1-10μs 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 photon 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.

ACKNOWLEDGMENTS

The authors thank J.K. Notthoff of McDonnell Douglas Astronautics Company for his assistance in the measurements at the White Sands Missile Range Linear and for helpful discussions.

REFERENCES