TEMPERATURE DEPENDENT GaAs MMIC RADIATION EFFECTS*

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ABSTRACT

The temperature dependence of pulsed neutron and flash x-ray radiation effects was studied in GaAs MMICs. Above room temperature the long term current transients are dominated by electron trapping in previously existing defects. At low temperature in the range 126 to 259 K neutron induced lattice damage appears to play an increasingly important role in producing long term current transients.

I. INTRODUCTION

In a previous study of combined pulsed neutron and flash x-ray (FXR) radiation effects on GaAs monolithic microwave integrated circuits (MMICs) it was found that the FXR pulse alone induces negative and positive long term drain current transients, the magnitude and duration of which depend on the trapping levels present in the particular substrates used to fabricate the MMICs and field effect transistors (FETs). Pulsed neutrons induce the same long term transients as the FXRs due to the accompanying gamma rays and also induce lattice damage that results in a decrease in drain current from carrier removal and mobility degradation. It appears from the pulsed neutron experiments that a small amount of the neutron induced lattice damage anneals out at room temperature because the drain current recovered in a period of about 100 ns. In the present paper the temperature dependence of both the prompt photocurrents and the long term transient currents were studied to separate neutron induced and FXR induced effects.

Pulsed neutron and combined radiation effects have been little studied in GaAs devices. Transient radiation effects resulting from flash x-rays and pulsed electrons have been reported separately, including in some cases temperature effects. In this paper we report on temperature dependent effects in the combined environment of pulsed neutrons and flash x-rays. Because there are many low temperature and high temperature applications of GaAs devices it is important to understand radiation effects outside of the normal operating temperature range.

The need to understand effects in the combined environment, the advantages over separate testing, and facilities used for the present experiments are discussed in Ref. 13 and 14. Figure 1 shows the typical Si photodiode voltage response of combined FXR (85 ns) and pulsed neutron (83 μs) pulses. The shape of the neutron pulse is due to accompanying gamma radiation that produces electron-hole pairs in GaAs but negligible displacement damage.

II. EXPERIMENTS

Both MMICs and discrete GaAs FETs were studied. This was necessary in order to separate transient radiation effects in the FETs from possible circuit responses. The design, fabrication, and performance of the MMICs studied are discussed in Reference 15. Ion implantation into low chromium doped liquid encapsulated Czochralski (LEC) substrates was used to form the active layer. Mesa etching was used for device isolation and to define the GaAs resistors. Gate definition with recessed 0.5 μm TiPtAu metallization was achieved by electron beam lithography. Ohmic contacts were formed with alloyed AuGe/NiAu. The capacitor dielectric was 2000 Å of silicon nitride deposited by plasma enhanced chemical vapor deposition and this dielectric was left in the gate area for passivation. Gold air bridges were used to connect the FET source pads and as interconnects to the top capacitor plates.

The transient effect of FXR ionizing radiation on a GaAs MMIC EG 8300 distributed amplifier at 30°C is shown in Fig. 2. In this paper “rad” refers to rad (GaAs). A positive drain current transient of amplitude and duration of approximately 1 mA and 30 μs, respectively, can also be deduced from these data. Positive gate and drain photocurrents are observed which arise from the very large number of electron-hole pairs created by the x-rays. Because a reverse gate photocurrent is observed, the radiation induced carrier concentration under the gate must be greater than -10¹⁸ cm⁻³ because this is approximately the carrier concentration at which a Schottky contact will become ohmic. The drain current also exhibited a positive long term transient of 30 μs, which is attributed to hole trapping in the substrate. This accounts for the fact that at the end of 8 μs ΔD is 1 mA, on the left in Fig. 2, and ΔD starts at 1 mA, on the lower right trace in Fig. 2.

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Fig. 2 - Transient change in gate current, $\Delta I_G$, and drain current, $\Delta I_D$, of GaAs MMIC EG8300, #33 at 30°C following an 85 ns flash X-ray (FXR) exposure of 9.2 krad, 1.1 $\times$ 10$^{11}$ rad/s.

Fig. 3 - Transient change in gate current, $\Delta I_G$, and drain current, $\Delta I_D$, of GaAs MMIC EG8300, #36 at 30°C following combined FXR (85 ns, 8.5 krad, 1 $\times$ 10$^{11}$ rad/s) and pulsed neutron (83 ps, 8.3 $\times$ 10$^{12}$ n/cm$^2$, 10$^{17}$ n/cm$^2$/s) exposure. FXR alone resulted in a positive long term transient of $I_D$ of 80 μs.

A quite different long term transient response was observed when the MMIC was exposed to combined FXR and pulsed neutron radiation at 30°C, as shown in Fig. 3. The positive gate and drain current photoresponses are again observed, but the drain current now exhibits a large negative long term transient of about 3 ms. Similar gate and drain photocurrent and drain long term transients were observed when an MMIC was irradiated at 30°C by an order of magnitude larger neutron pulse alone, as shown in Fig. 4. The pulsed neutron induced negative 3 ms transient is shown on a longer time scale in Fig. 5. Under FXR irradiation alone MMIC #36 exhibited a positive long term transient of 80 μs duration, which is masked by the pulsed neutron prompt response. The 3 ms negative transient is the result of pulsed neutron irradiation; it was observed only when a neutron pulse was used as was demonstrated with separate neutron pulses. Because the FXR pulse of ionizing radiation resulted in a positive 80 μs drain current transient, it is unlikely that the accompanying gamma radiation during the neutron pulse is responsible for the long term negative drain current transient. Transient carrier

Fig. 4 - Transient change in gate current, $\Delta I_G$, and drain current, $\Delta I_D$, of GaAs MMIC EG8300, #34 at 30°C following a 71 μs neutron pulse of 2.3 $\times$ 10$^{14}$ n/cm$^2$, 3.2 $\times$ 10$^{18}$ n/cm$^2$/s.

Fig. 5 - Transient change in drain current $\Delta I_D$, of a GaAs MMIC EG8300 #35 at 30°C following a combined FXR (85 ns, 1 $\times$ 10$^{11}$ rad/s) and pulsed neutron (83 μs) exposure. FXR alone resulted in a positive long term transient of 100 ms.
removal is another explanation, because, as shown previously, carrier removal resulting from displacement damage predominates over mobility degradation for neutron irradiation of GaAs. Therefore, the negative long term drain current transient induced by pulsed neutron irradiation at 30°C is attributed to carrier removal resulting from lattice displacement damage that anneals between 3-100 ms. The effect of raising the temperature is to reduce the FXR long term transients both in magnitude and duration. Thus the 80-μs transient at 30°C in Fig. 2 was much reduced in amplitude and reduced to 40 μs at 150°C. This is the expected result of holes trapped in previously existing defects in the GaAs substrate or near interfaces,¹¹ the holes having been created as electron hole pairs by the FXR pulse.

Lowering the temperature appeared to primarily effect the neutron induced negative transient. This effect was studied in discrete GaAs FETs and MMICs. However, it was not possible to study the same FETs as in the EG8300 circuit because none were included in discrete form on the mask set and individual FETs could not be bonded out in the distributed amplifier. However, FETs were bonded out in two stage amplifiers EG8014. The fabrication of these circuits was the same as the EG8300 described above; only the circuit design was different. These FETs had a gate width of 900 μm, compared to a total gate width of 756 μm for entire four FET distributed amplifier EG8300, and the saturated drain current was about 20% higher than the MMIC EG8300. Figure 6 shows the results of combined pulsed neutron and FXR radiation on a discrete GaAs FET at 40°C. In (A) the large positive increases in drain (ΔD) and gate (ΔG) currents are the prompt photoresponse due primarily to electron hole pairs created by the gamma rays that accompany the pulsed neutrons. The short increase and noise at the beginning of the peak is due to the 85 ns FXR pulse. In both Figures A and B the time scale unit is μs. Note that ΔD exhibits a long term negative transient of about 4 mA. That this negative transient is the result of pulsed neutron irradiation is shown by the response of the FET to only FXR irradiation in (B). A ΔD negative transient of about the same magnitude is again induced, attributed to backgating due to charge trapping in the substrate and at interfaces,¹¹ but the duration is only about 0.2 ms. These results are shown more clearly in Figure 7. In (a) it is shown that the neutron pulse at 40°C only induces the long term negative ΔD transient. Figure 7(b) shows that a FXR pulse only induces a negative ΔD transient of about 0.1 ms. In Fig. 7(c) it is shown that the negative ΔD transient induced by pulsed neutron irradiation has a duration of about 100 ms.

This long term neutron transient was studied in more detail by lowering the temperature and using separate pulsed neutron, FXR, and combined pulses. It was not observed down to -147°C using only the FXR pulse. With both the pulsed neutron and combined pulses this transient increased with decreasing temperature, as shown in Table. 1. A similar temperature dependence was found for GaAs EG8300 MMICs. If this negative transient is induced by electrons trapped temporarily in neutron induced defects, the duration would be determined by two possible temperature dependent processes: (1) the anneal time of the neutron induced defects, or (2) the trapping time of the electrons, as measured in transient radiation effects experiments.²

III. DISCUSSION

Pulsed neutron transient effects have been reported in GaAs JFETs by Zuleeg et al.,¹⁷ who attributed 3.5 minute transients to radioactive decay, and Sander et al.¹⁸ and McMurray et al.¹⁹ in Si devices, who attributed the effect to short term room temperature anneal of neutron induced lattice damage. The data of Sander et al.¹⁸ show that for Si solar cells, the annealing factor is largest at about 1 ms and decreases out to 100 ms. Both the EG8300 MMIC and the discrete FETs exhibited increasing long term transient times with decreasing temperature and these data support the interpretation of short term neutron induced defects in GaAs. Another possible interpretation is that transient effects arise...
from neutron induced radioactivity in the GaAs or the device metallizations. For example, As\textsuperscript{75} has an excited state of 16.5 ms and relaxes by gamma emission. However, the cross section to induce sufficient excited species may not be large enough at the neutron fluences used thus far because a positive 16.5 ms transient has not yet been observed.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Temperature (°C) & Duration of Transient (ms) \\
\hline
40 & 100 \\
-14 & 250 \\
-95 & 300 \\
-147 & 350 \\
\hline
\end{tabular}
\caption{Temperature Dependence of the Pulsed Neutron Induced Long Term Negative Drain Current Transient, $\Delta I_D$, of GaAs FET Type 8014}
\end{table}

Fig. 7 - Transient change in drain current, $\Delta I_D$, of GaAs FET 8014-17 at 40°C under normal bias following: (a) 80 μs neutron pulse, (b) FXR pulse, and (c) combined neutron pulse and FXR. The time scale unit for all three figures is ms.

IV. CONCLUSIONS

The temperature dependence of combined pulsed neutron and FXR transient radiation effects were studied in GaAs MMICs and discrete GaAs FETs. Both pulsed neutrons and flash x-rays induce photocurrents in the gate and drain at the highest levels of irradiation (2.3 x 10\textsuperscript{14} n/cm\textsuperscript{2}, 3.2 x 10\textsuperscript{18} n/cm\textsuperscript{2}/s, 9.2 krad per pulse, 1.1 x 10\textsuperscript{11} rad/s). The FXR pulse alone also induces negative and positive long term transients, the magnitude and duration of which depend on the temperature and trapping levels present in the particular substrate used to fabricate the MMICs and FETs. Pulsed neutrons induce the same long term transients as the FXRs due to the accompanying gamma rays and also induce lattice damage that results in a decrease in drain current from carrier removal and mobility degradation. It appears from the pulsed neutron temperature dependence experiments that a small amount of the neutron induced lattice damage anneals out in the temperature range of -147° to +150°C. The results demonstrate the importance of combined radiation effects experiments over separate pulsed neutron and FXR measurements. Up to now FXR and total fluence measurements have been used almost exclusively to simulate a nuclear event. Combined effects were not studied. With the devices studied in the present experiments, combined effects appear to be important in determining the temperature dependence of the radiation induced prompt photocurrents and long term transients. For example, pulsed neutron irradiation produce lattice displacements, which act as electron and hole traps, can capture carriers produced by the accompanying ionizing gamma radiation and/or separate FXR pulse. The resulting trapped charge may then produce backgating of the drain current which decays with a characteristic time constant as the carriers are emitted from the trapping levels and as the trapping levels anneal out.

V. REFERENCES


