RADIATION EFFECTS IN InP JFETs

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Abstract

Transient and total dose radiation effects were studied in InP JFETs under bias conditions. The transient responses in drain current, Ig, and output power, Pd, at 4.5 GHz following 50 ns pulses of 40 MeV electrons were small up to 1.7x10^11 rad(InP)/s. The long term transient response is postulated to result from substrate trapping of radiation induced carriers and consequent backgating. No measurable drift in Ig was observed following exposure to 40 MeV pulsed electrons, 1 MeV electrons from a Van de Graaff, or gamma rays from a Co60 source. No significant degradation was found in Ig or Pd up to a total dose of 8x10^9 rad (InP). The hardness level for 1 MeV gamma irradiation is greater than 10^7 rad and for 1 MeV electron irradiation it is greater than 8x10^9 rad, exceeding that of GaAs by more than an order of magnitude. Total dose degradation is the result of carrier removal.

Introduction

The development of InP junction field effect transistors (JFET) by both Zn diffusion and ion implantation has recently been reported. It is the purpose of this paper to report on the high radiation tolerance of these new types of devices to both long-term transient ionizing radiation and total dose ionizing radiation.

Description of InP JFETs

The two types of InP JFETs studied are shown in Fig. 1 by cross section and top view design. These Zn diffused and Be implanted JFETs were fabricated by the methods found in references 1 and 2, respectively. The Zn-diffused device had relaxed geometry design with a gate length of 2-3 μm while the Be implanted device was designed to operate at X-band and had a 1 μm gate length. In both cases, the active channel N layer was formed by Si ion implantation. Figure 2 contains some further fabrication details of the Be implanted device.

![Fig. 1. Cross section and top view layout of Be implanted and Zn diffused InP JFETs.](image)

![Fig. 2. Be implanted InP JFET showing schematically total dose radiation effect mechanism and transient radiation effect mechanism.](image)

Table I. Planar Be Implanted InP JFET Microwave Performance

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Insertion Gain</th>
<th>Power Output (3 dB Gain)</th>
<th>Scaled Power Output (3 dB Gain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 GHz</td>
<td>13.1 dB</td>
<td>300 mW</td>
<td>1 W/mm</td>
</tr>
<tr>
<td>8.0 GHz</td>
<td>9.4 dB</td>
<td>200 mW</td>
<td>.66 W/mm</td>
</tr>
</tbody>
</table>

Total Dose Ionizing Radiation Effects

Total dose radiation effects under high current bias conditions were measured using a Co60 source up to 10^9 rad (InP) and 1 MeV electrons from the NRL Van de Graaff accelerator from 3x10^7 to 8x10^9 rad (InP). As shown in Fig. 3, up to 1x10^9 rad IgS degraded by only 8% and the gain at 4.5 GHz exhibited no measurable change under gamma irradiation. The total dose exposure was then continued at a higher dose rate of 5x10^9 to 1x10^10 rad/s using 1 MeV electrons. No significant degradation was observed out to a total dose of 8x10^9 rad. We conclude that the hardness level for InP JFETs is greater than 1x10^9 rad for Co60 gamma irradiation and greater than 8x10^9 rad for 1 MeV electron irradiation. This compares favorably with GaAs FETs which were reported to have a 20% degradation IgS hardness level of 3x10^7 rad when irradiated under identical conditions. As with the GaAs FETs, the degradation mechanism is postulated to be carrier removal. This is indicated schematically in Fig. 2. These results also compare favorably to those reported for InP MISFETs. As shown in Fig. 4, instabilities in the I-V characteristics were observed pre- and post-irradiation indicating trapping of injected electrons and holes in the gate oxide. At low total dose levels of 10 to 50 krads, Vth increased to higher positive values resulting from the trapping of negative charge in the oxide. As the total dose level increased above 100 krads (SiO2), the radiation induced positive trapped charge dominated, thereby inducing a negative threshold voltage shift typical of irradiated n-channel Si MOS devices. The radiation hardness level for the present...
state of InP MISFET development is approximately $1 \times 10^3$ rad. Another advantage of the InP JFET is that no drift component was introduced in the drain current following gamma or electron irradiation whereas the InP MISFETs exhibited large long-term drifts lasting longer than 30 min, as shown in Fig. 4.

Fig. 3. Total dose radiation effects in Zn diffused InP JFET exposed to ionizing radiation under normal bias conditions.

Fig. 4. Total dose radiation effects in an InP MISFET exposed to Co60 gamma irradiation under bias conditions for various times after exposure for device 66.

Transient Radiation Effects

Transient radiation effects of the change in drain current, $I_{DS}$, and output power, $P_O$, at 4.5 GHz were made at the NRL Linac, as previously described. The devices were irradiated by 50 ns pulses of 40 MeV electrons under bias conditions while operating at 4.5 GHz. Changes in $I_{DS}$ were measured with a high speed current probe and $P_O$ were recorded on film using a dual trace oscilloscope with a time resolution down to 1 μs.

Figure 5 shows the transient radiation induced changes in $I_{DS}$ and $P_O$ for a Be implanted JFET following a 50 ns pulse of 40 MeV electrons while operating under normal bias conditions. At 4.5 GHz the gain was 4.0 dB. No significant transient in $I_{DS}$ or $P_O$ were observed immediately following the pulse of 2.0 Krad ($4.1 \times 10^{10}$ rad/s) as shown on the left (2 μs/div). The figure on the right (100 ms/div) shows that there was no measurable long-term transient under normal bias conditions. Transients were observed in devices biased at low current, as shown in Fig. 6 for a Be implanted JFET. At a drain current of 18 mA this device still exhibited a gain of 2.0 dB. As shown in the left figure, both $I_{DS}$ and $P_O$ experienced a transient decrease after receiving a pulse of 6.5 Krad ($1.3 \times 10^{11}$ rad/s). The recovery time, $T_r$, defined as the time required for $I_{DS}$ or $P_O$ to return to 90% of the baseline value, was about 10 ms.

![Fig. 5. Transient radiation induced change in $I_{DS}$ and $P_O$ at 4.5 GHz of a Be implanted InP JFET following a 50 ns pulse of 40 MeV electrons.](image)

![Fig. 6. Transient radiation induced change in drain current, $I_{DS}$, and output power, $P_O$, at 4.5 GHz of a Be implanted InP JFET following 50 ns pulse of 40 MeV electrons.](image)

Because InP JFETs are similar to GaAs FETs, except for the P-N junction gate, we postulate that the long-term transient effect shown in Fig. 6 arises from the same mechanism as in GaAs FETs. This mechanism, discussed in ref. 7, is shown schematically in Fig. 2. When high energy ionizing radiation passes through the device, as is the case with 40 MeV electrons, a few percent of the electrons or holes created by the high energy electrons, are trapped in the substrate. In Fig. 2, we show the case of electron trapping, which gives rise to negative ($I_{DS}$ decrease) transients. Because the substrate is very thick (typically 600 μm) compared to the active channel (0.2 μm), charge stored temporarily in the substrate can have a significant affect on the channel current. As shown in ref. 7, charge stored in the substrate can be represented as a surface charge at the active channel/substrate interface, of density

$$N_{SS} = \frac{+ Na}{3} \left[ 1 - 3V_g/V_p + 2(V_g/V_p)^{3/2} \right] \frac{\Delta I_{DS}(0)}{I_{DS}(0-)}$$

(4)

where the + or - refers to hole or electron trapping, respectively, N is the channel carrier concentration, a is the channel depth, $V_g$ is the gate bias, $V_p$ is the
pinchoff voltage, $\Delta I_{DS}(0)$ is the change in drain current immediately following the pulse, and $I_{DS}(0)$ is the quiescent current level just prior to irradiation. This effective surface charge density induces a depletion region at the bottom of the channel and in effect is a backgate. As the trapped charge is released with a characteristic time constant depending on the activation energy of the trapping level and the temperature, this back gate effect is reduced and the drain current recovers.

Figure 7 shows the transient effect in a Zn diffused JFET biased at low current following pulse of 8.9 Krad (1.8x10^{11} rad/s). At an input power of $P_{IN} = 2$ mW, the device exhibited a gain of 2.9 dB. By comparing the figure on the left with the response at the right of 0 rad (electron beam deflected before entering the radiation exposure room) we see that only a small transient, with recovery time of 30 ns, was exhibited by $I_{DS}$ and $P_{IN}$. Under normal bias conditions, as shown in Fig. 8 for another Zn diffused JFET, no measurable long term transient was observed between 2 ms and 1 is after a pulse of 6.0 Krad (1.2x10^{11} rad/s).

![Fig.7. Transient radiation induced change in drain current, $I_{DS}$ and output power, $P_{IN}$ at 4.5 GHz of a Zn diffused InP JFET following a 50 ns pulse of 40 MeV electrons.](image)

![Fig.8. Transient radiation induced change in drain current, $I_{DS}$ and output power, $P_{IN}$ at 4.5 GHz of a Zn diffused InP JFET following a 50 ns pulse of 40 MeV electrons.](image)

Table II summarizes the long-term transient radiation response of InP JFETs irradiated by 50 ns pulses of 40 MeV electrons under normal bias operating conditions. Only small transients were observed, even up to 1.7x10^{11} rad/s.

Larger transients were observed at low current bias conditions, summarized in Table III. This is the expected result based on the model of substrate trapping and consequent backgating. Two trap levels evidently predominate in the substrates used to fabricate these devices, as evidenced by the recovery times of 50 ns and 5 ms. From Table III, we conclude that at low current bias conditions the hardness level, considered to be a 20% change in $I_{DS}$ or $P_{IN}$, is 2x10^{11} rad/s. Under normal conditions, the transient radiation hardness level is much higher.

![Fig.9. Transient radiation response of drain current ($I_{DS}$) vs time for InP MISFET No. 2H biased under low current operating conditions ($V_{DS} = 4.0$V, $V_{G} = V_{th}$, $I_{DS}(0) = 2.5$ mA prior to first electron pulse) following 50 ns pulse of 40 MeV electrons (2.0 Krad, 4.0x10^{10} rad/s), change in drain current $\Delta I_{DS} = 0.8$ mA after first pulse, 2 μs per div. on the left and remaining drift component $\Delta I_{DS} = 4.3$ mA after fifth pulse, 5s per div. on the right.](image)

### Table II. Long-term Transient Radiation Response of InP JFETs Irradiated by 50 ns Pulses of 40 MeV Electrons While Under High Current Bias Conditions ($V_{DS} = 6$V, $V_{G} = -3$V)

<table>
<thead>
<tr>
<th>Device</th>
<th>$I_{DS}$ (mA)</th>
<th>$\Delta I_{DS}$ (mA)</th>
<th>$\Delta I_{DS}/I_{DS} (%)$</th>
<th>Dose Rate (Rad/s)</th>
<th>Recovery Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnInP-B</td>
<td>70.0</td>
<td>0</td>
<td>0</td>
<td>4.6 x 10^{10}</td>
<td>-</td>
</tr>
<tr>
<td>ZnInP-C</td>
<td>80.0</td>
<td>-0.8</td>
<td>-1.0</td>
<td>1.7 x 10^{11}</td>
<td>30 μs</td>
</tr>
<tr>
<td>ZnInP-D</td>
<td>80.0</td>
<td>-1.2</td>
<td>-1.5</td>
<td>1.2 x 10^{11}</td>
<td>30 μs</td>
</tr>
<tr>
<td>BeInP-B</td>
<td>82.0</td>
<td>0</td>
<td>0</td>
<td>5.9 x 10^{10}</td>
<td>-</td>
</tr>
<tr>
<td>BeInP-C</td>
<td>70.0</td>
<td>0</td>
<td>0</td>
<td>4.1 x 10^{10}</td>
<td>-</td>
</tr>
</tbody>
</table>

These results compare favorably with transient radiation effects in GaAs FETs and also with InP MISFETs. Figure 9 shows the typical transient response of an InP MISFET biased under low current conditions following a 50 ns pulse of 40 MeV electrons (2.0 Krad, 4.0x10^{10} rad/s). This transient response is thought to be the result of charge trapping in the gate oxide. The radiation induced charge trapping in the gate oxide persists for periods of 30 min and is responsible for the drift component shown on the right in Fig. 9. Table IV compares the transient radiation response of the InP JFETs and MISFETs. At both low and high current bias conditions, the relative transient $\Delta I_{DS}/I_{DS}$ was much larger in the MISFETs. Also, the radiation induced drift component in $I_{DS}$ was present in all MISFETs, was not observed in the JFETs.

### Conclusions

Total dose gamma and electron radiation effects were measured in InP JFETs developed at the Naval Research Laboratory and compared to previously reported
effects in GaAs FETs and InP MISFETs. The JFET hardness level (defined as a 20% change in drain current or output power) is greater than 10^8 rad. This is five orders of magnitude higher than for InP MISFETs, which also exhibited a drift component in the drain current that persisted for longer than 30 min. When exposed to 1 MeV electrons, the hardness level was concluded to be greater than 8x10^8 rad. This result compared favorably with GaAs FETs which have a hardness level of 3x10^7 rad when irradiated under identical conditions. Total dose degradation in the InP JFETs is postulated to result from carrier removal.

Transient radiation effects were studied using 50 ns pulses of 40 MeV electrons. Only small changes in drain current or output power were induced in the JFETs at normal operating conditions or at reduced current where the devices are most susceptible to transient effects. The hardness level for low current bias conditions was found to be 2x10^4 rad/s and is much higher at normal bias conditions. These results compare favorably to those observed in GaAs FETs, and are a large improvement over results observed in InP MISFETs. The InP MISFET hardness level is below 10^10 rad/s even at high current bias conditions and these devices exhibited a drift component in Ids following a pulse of ionizing radiation that persists for longer than 5 min. No drift component was observed in the InP JFETs. The long term transient effect in InP JFETs is postulated to result from charge trapping in the substrate and consequent backgating.

References