Annaling of Proton and Alpha Particle Damage in Au-W/β-Ga₂O₃ Rectifiers

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Vertical geometry Ga₂O₃ rectifiers were irradiated with 18 MeV alpha particles to fluences of 1–3 × 10¹⁵ cm⁻² and then annealed to establish the thermal stability of the radiation damage. The rectifiers employed Au/W rectifying contacts to achieve the requisite thermal stability to allow for annealing studies. The carrier removal rates were ~900 cm⁻² for the α-particles and ~200 for the protons. Annealing at 500°C was found to restore the carrier concentration in the α-particle irradiated devices, while 450°C annealing brought substantial recovery of the proton irradiated devices. This is a similar temperature range as established for annealing of plasma-induced damage in Ga₂O₃, suggesting a common origin of point defects, predominantly Ga vacancies and their complexes. The reverse breakdown voltages and diode on/off ratios are also significantly recovered by annealing after irradiation.

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Experimental

The diodes were fabricated on 10 µm Si-doped (2.7 × 10¹⁶ cm⁻³) epitaxial layers grown by Halide Vapor Epitaxy (HYPE) on (001) oriented 650 µm β-phase Sn-doped (n = 3.6 × 10¹⁴ cm⁻³) Ga₂O₃ with edge-defined film-fed growth method (Novel Crystal Technology). A back side contact (20 nm/80 nm Ti/Au) was formed using electron beam (E-beam) evaporation followed by 30 second rapid thermal annealing at 550°C in nitrogen ambient using an SSI SOLARIS 150 rapid thermal annealer. The sample surface was then treated in O₃ for 20 minutes to remove hydrocarbon and other contamination species.

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Figure 1. SRIM simulation of vacancy distribution in Ga$_2$O$_3$ subject to different fluences of 18 MeV alpha particles or 10 MeV protons. The y-axis is the relative magnitude of the vacancy density.

The projected range of the alpha particle and protons beams was calculated using the Stopping and Range of Ions in Matter (SRIM) program and is 85 and 340 µm, respectively, as shown in Figure 1. This means the alpha particles and protons completely traverse the drift region of the rectifiers and come to rest in the substrate. In other words, the damage is mainly beyond the drift region.

To gain some perspective of how much damage remained in the drift region of the rectifiers, we thinned down some of the samples by polishing removal of most of the substrate until just 75 µm thickness remained and then metallized the back side. Schematics of the full thickness and thinned rectifiers is shown in Figure 2. Table I summarizes the effect of both types of radiation exposure on the Schottky barrier height, diode ideality factor and on-state resistance for the as-irradiated and annealed conditions. The differences in these parameters are generally smaller than for the I-V, C-V and on/off ratios of the rectifiers, so we focus on that data in the subsequent sections.

Results and Discussion

Alpha particle irradiated rectifiers.—Figure 3 shows the forward I-V characteristics for the rectifiers before and after the $10^{13}$ cm$^{-2}$ (top) or $3 \times 10^{13}$ cm$^{-2}$ (bottom) floures and after subsequent annealing at 400–500°C.

The recovery in carrier concentration as a function of annealing was consistent with previous work in other wide bandgap semiconductors, where both mobility and carrier density are observed to diminish as a result of the introduction of radiation damage. The thinned diodes suffer less current reduction for the low dose, but the higher dose suppresses current to a similar level as in the regular thickness devices since the damage is basically saturated. It is noteworthy that annealing at 500°C for 5 min is basically sufficient to restore the forward current. Previous reports have shown that plasma-induced damage in Ga$_2$O$_3$ also anneals in this temperature range, suggesting a common origin of point defects. In particular, Ga$_2$O$_3$ is found to be dominated by the presence of Ga vacancies, with $V_{Ga}$.

Figure 4 shows the reverse current characteristics for the higher dose samples. Assuming a one-sided abrupt diode, the corresponding breakdown voltage, $V_B$, is proportional to $E_0^{1/2} \xi/2e$, where $E$ is the electric field at breakdown, and $\xi$ is the permittivity of the semiconductor. Thus, the reduction in carrier density will cause an increase in breakdown voltage. Once again, annealing at 500°C is sufficient to restore the initial breakdown characteristics.

The recovery in carrier concentration as a function of annealing was obtained from C-V measurements, with the results shown in Figure 5 in the form of C$^{-2}$-V plots. The drift layer became fully depleted and $3 \times 10^{13}$ cm$^{-2}$ (bottom) fluences and after subsequent annealing. The main effect of the irradiation is to reduce the forward current. Since the total forward current is proportional to $e\mu_nE$, where $e$ is the electronic charge, $\mu_n$ is the electron mobility, and $E$ is the electric field strength at a given bias voltage, then the reduction in forward current is due to a reduction in both mobility and carrier concentration. The latter through formation of deep trapping states that remove electrons from the conduction band. This is consistent with previous work in other wide bandgap semiconductors, where both mobility and carrier density are observed to diminish as a result of the introduction of radiation damage.

Figure 2. Schematic of conventional (left) and thinned-down (right) rectifier structures.
Table I. Summary of barrier heights, ideality factors and on-state resistances.

<table>
<thead>
<tr>
<th>Irradiation Dose</th>
<th>Sample</th>
<th>Schottky Barrier Height (eV)</th>
<th>Ideality Factor (-)</th>
<th>On Resistance (mΩcm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Reference</td>
<td>0.77</td>
<td>1.15</td>
<td>4.9</td>
</tr>
<tr>
<td>Alpha 10¹³</td>
<td>Irradiated</td>
<td>0.68</td>
<td>1.23</td>
<td>17.8</td>
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<tr>
<td></td>
<td>450°C 5 min anneal</td>
<td>0.7</td>
<td>1.2</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>400°C 5 min anneal</td>
<td>0.65</td>
<td>1.29</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Thinned down</td>
<td>0.74</td>
<td>1.12</td>
<td>745</td>
</tr>
<tr>
<td>Alpha 3 × 10¹³</td>
<td>Irradiated</td>
<td>0.66</td>
<td>1.28</td>
<td>19.0</td>
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<tr>
<td></td>
<td>450°C 5 min anneal</td>
<td>0.79</td>
<td>1.12</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>500°C 5 min anneal</td>
<td>0.79</td>
<td>1.12</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>Thinned down</td>
<td>0.74</td>
<td>1.12</td>
<td>16.9</td>
</tr>
<tr>
<td>Proton 10¹⁴</td>
<td>Irradiated</td>
<td>0.74</td>
<td>1.12</td>
<td>13.1</td>
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<tr>
<td></td>
<td>450°C 5 min anneal</td>
<td>0.76</td>
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<td>6.4</td>
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<tr>
<td>Proton 3 × 10¹⁴</td>
<td>Irradiated</td>
<td>0.74</td>
<td>1.12</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>450°C 5 min anneal</td>
<td>0.82</td>
<td>1.09</td>
<td>7</td>
</tr>
</tbody>
</table>

for both the alpha fluences, but recovered with annealing. Consistent with the I-V data, the carrier concentration is seen to be restored to essentially its initial level after 500°C annealing. The starting carrier concentration in the drift region of the as-fabricated diodes was 2.69 \times 10^{16} \text{cm}^{-3} and in the higher dose samples, this recovered to 1.33 \times 10^{16} \text{cm}^{-3} for annealing at 450°C and 2.67 \times 10^{16} \text{cm}^{-3} for 500°C annealing.

The diode on/off ratio is another figure-of-merit. Figure 6 shows this ratio when switching from 2V forward to the reverse bias shown on the x-axis for the 10¹³ (top) and 3 \times 10¹³ cm⁻² (bottom) fluences and after subsequent annealing. The on/off ratio is particularly susceptible to change with the introduction of radiation damage, decreasing by 6–8 orders of magnitude depending on the alpha particle fluence. However,
were much less pronounced than for the alpha particle irradiation. The recovery time was ~20 ns.

The thermal stability of radiation damage in Ga2O3 vertical rectifiers was established for alpha and proton-irradiation. The I-V, C-V and on/off ratios are all significantly degraded by moderate fluences of these forms of radiation, but can be essentially recovered by annealing at 450°C for 5 mins. Other parameters such as Schottky barrier height, ideality factor and reverse recovery char-

Conclusions

The thermal stability of radiation damage in Ga2O3 vertical rectifiers was established for alpha and proton-irradiation. The I-V, C-V and on/off ratios are all significantly degraded by moderate fluences of these forms of radiation, but can be essentially recovered by annealing at 450°C for 5 mins. Other parameters such as Schottky barrier height, ideality factor and reverse recovery char-
characteristics are less affected by radiation damage. The commonality of annealing stages between these ionizing forms of radiation and plasma-induced damage in Ga$_2$O$_3$ suggest a common origin of point defects. In the vertical geometry devices studied here, the damage created in the drift region is most important in determining the relative degradation of device performance, as evidenced by our experiments where removed the end-of-range damage in the substrate.

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**References**
