Correspondence

The Restructuring of Aluminum on Gallium Arsenide

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Abstract—The restructuring of aluminum (Al) on GaAs has been observed on low-power GaAs field-effect transistors (FETs) and on special test structures. For $4 \times 10^4$ heating and cooling cycles, temperature swings as low as 90°C produced restructuring. Restructuring is weakly dependent on deposition temperature, and no change in the Al resistance was observed.

I. INTRODUCTION

Microwave power GaAs FET's for use in radar systems will need to withstand $10^8$ to $10^{12}$ cycles of heating and cooling during system lifetime. If Al gates are used, the difference between the thermal expansion coefficient of the Al and the underlying GaAs creates strains in the Al which could lead to failure. This potential failure mechanism, termed restructuring, will not show up in conventional temperature-stressed life testing unless worst case thermal cycling (long-pulse low-duty cycle) is employed. The restructuring of Al on SiO$_2$ has been well documented [1] and has been shown to be a purely mechanical effect involving the plastic deformation of Al under repeated heating and cooling cycles. The gross indication of restructuring is a roughening of the Al surface which can be seen at low optical magnification as a darkening of the affected metal. The most important stress factors are the temperature swing $\Delta T$ and the number of heating and cooling cycles $N$

State-of-the-art 1 W X-band FET's have gains of about 5 dB and efficiency of about 30 percent along with continuous wave (CW) thermal resistance of about 50°C W. As a consequence, it can be deduced that for long-pulse low-duty factor operation a $\Delta T$ of 100°C is typical.

In this correspondence, emphasis is placed on Al degradation that results from temperature cycling, as distinguished from such effects as electromigration or Al–GaAs chemical interactions that arise from long-time operation at high temperature and that show up in conventional accelerated life tests. We investigated the restructuring of Al on GaAs using a commercial [2] four-micron gate length low-power GaAs FET. A special test structure fabricated at the Naval Research Laboratory was also used.

II. RESTRUCTURING OF FET GATE

One-millisecond 1.5 W pulses at 10 percent duty factor were applied to the drain of commercial devices with the gates open-circuited (no gate current). The temperature excursions were estimated in a side experiment in which the pulsed thermal resistance was measured by a well-known electrical technique [3]—the gate was forward biased at constant current and the temperature dependence of the gate voltage (about 2 mV°C) was used to measure the pulsed thermal resistance. Restructuring was observed at low optical magnification as a darkening of the Al film, usually near the center of the gate. Figs. 1(a) and (b) show SEM pictures of restructuring on two devices. The device shown in Fig. 1(a) underwent $3.5 \times 10^5$ cycles with a $\Delta T$ of 160°C. The device in Fig. 1(b) was cycled $8 \times 10^3$ times, and $\Delta T$ was 175°C. In the latter case, the total time at temperature was less than 8 min. This fact, along with the zero gate current and the relatively low-peak temperature, tends to eliminate electromigration, corrosion, etc., as causes of the degradation.

III. SPECIAL TEST STRUCTURE

The Naval Research Laboratory test structure is shown in Fig. 2(a). The Al stripe is 1 mil wide and about 1 micron thick. The Al was vacuum evaporated onto (100) oriented chromium doped insulating GaAs at substrate temperatures of 25, 200, and 350°C. The deposition rate, about 400 Å/s, and cleaning procedure were chosen to give hillock-free films with good adhesion according to the Scotch-tape test. Good adhesion, of course, essential for structuring tests.

A detailed study of the as-deposited films has not been made. The room-temperature films have a particle size of about 500 Å as measured by X-ray line width. The two higher temperature films have a strong (100) orientation as determined by reflection electron diffraction, and the 350°C film appears to be epitaxial.

The experimental procedure was similar to that of Philofsky et al. [1] in their studies of the restructuring of Al on SiO$_2$. Heating pulses are applied to the pads at the ends of the stripe, and the temperature is determined by observing the change of resistance during the pulse on an oscilloscope.

Table I contains the data of greatest interest which concerns the lowest $\Delta T$ at which restructuring was observed. At higher $\Delta T$, restructuring was observed on other samples at a lower number of cycles. For example, a room-temperature deposit showed restructuring after only $3 \times 10^3$ cycles with a $\Delta T$ of 140°C (sample 6). No significant change in stripe resistance was observed even for the heavily restructured samples such as that of Fig. 2(a), and no sample exhibited restructuring for $\Delta T$ less than 88°C. Fig. 2 shows the optical and SEM appearance of samples referred to in Table I or the text.

Manuscript received April 1, 1978; revised July 10, 1978. This work was supported in part by the Naval Electronic Systems Command. The authors are with the Naval Research Laboratory, Electronics Technology Division, Washington, DC 20375.

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Fig. 1. Two Plessey transistors, gate length 4 microns.

TABLE I

<table>
<thead>
<tr>
<th>Deposition Temperature °C</th>
<th>Number of Cycles</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>95</td>
<td>9.3x10^5</td>
</tr>
<tr>
<td>200°C</td>
<td>88</td>
<td>4.0x10^4</td>
</tr>
<tr>
<td>350°C</td>
<td>100</td>
<td>9.3x10^3</td>
</tr>
</tbody>
</table>

IV. SUMMARY AND CONCLUSIONS

Al films on GaAs may reconstruct at ΔT as low as 90°C. No systematic dependence on deposition temperature nor change in resistivity was observed. The Al-GaAs system is more resistant to restructuring than the Al-SiO$_2$ system. Philofsky et al. [1] noted restructuring in the latter system at ΔT as low as 45°C. This is probably due to the better thermal coefficient of expansion match in the Al-GaAs system.

The implications of GaAs FET device reliability in the pulsed RF mode are not clear. On the one hand, ΔT reported here appear realistic in reference to possible real world operation of GaAs FET's. On the other hand, some power FET's have a silicon nitride overcoat [4] that may well inhibit restructuring. Furthermore, restructuring severe enough to produce drastic cosmetic effects does not necessarily cause device failure. However, the importance of this effect in gauging reliable device operation for military purposes cannot be minimized.

REFERENCES