Elevated Temperature Stability of GaAs Digital Integrated Circuits

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***Abstract*—The elevated temperature stability of a commercial GaAs enhancement-depletion-mode MESFET process has been characterized; the observations made are relevant to device operation at elevated temperatures, to efforts to do optoelectronic integration on GaAs integrated circuits by selective-area epitaxial growth, and to long term circuit and device reliability. Although the transistor electrical characteristics are stable for up to five h at 500°C, a metallurgical reaction between the interconnect metal $AlCu_x$ core and WN_x claddings has been identified which limits circuits to five h at 470°C. This later reaction proceeds with an activation energy of 3.5 eV and results in a 15-fold increase in interconnect metal sheet resistance. A geometry-dependent increase in ohmic contact resistance is seen at somewhat higher temperature which is ascribed to the penetration of aluminum-containing compounds to the ohmic contact edge.**

I. Introduction

THE optical device quality in optoelectronic integrated circuits formed by selective-area growth depends strongly on the epitaxial growth temperature [1]. This temperature is limited by the thermal stability of the underlying electronics. The MESFET thermal cycle response of the Vitesse HGaAs2 process has been previously studied [2]. It was observed that MESFET's were stable after 3 h at 500°C, but that increased source resistance resulted in performance degradation at higher temperatures. This paper describes an extensive study of the elevated temperature stability of the current Vitesse HGaAs3 process. The understanding gained of the degradation processes at elevated temperatures is relevant not only to setting the time-temperature bounds on the epitaxial growth process, but also to the operation of these circuits at elevated temperatures and to their long term stability at all temperatures.

II. Experimental

Electrical test structures located on Vitesse HGaAs3 process control monitor (PCM) test bars were measured before and after elevated temperature thermal cycles. Gate metal, ohmic metal and interconnect metal levels 1 through 3 sheet resistances were determined by the measurement of metal snake resistors. Metal-to-metal and metal-to-implant resistances per contact were determined from contact string resistor measurements. Large and small TLM structure resistance measurements allowed the extraction of the ohmic-contact and implant-sheet resistance. I-V characteristics of enhancement- and depletion-mode MESFET's of varying length and width were measured and their transconductance (g_m), saturation current ($I_{\rm sat}$), and source resistance (R_s) were extracted for each of nine different devices. In addition, Schottky-diode barrier height (ϕ_b) and ideality (n) were extracted for three different DFET's. Lastly, the oscillation period of a 23-stage direct coupled FET logic (DCFL) ring oscillator, with beta ratio of ten, was measured. Thermal cycles were performed in nitrogen ambient as in [2].

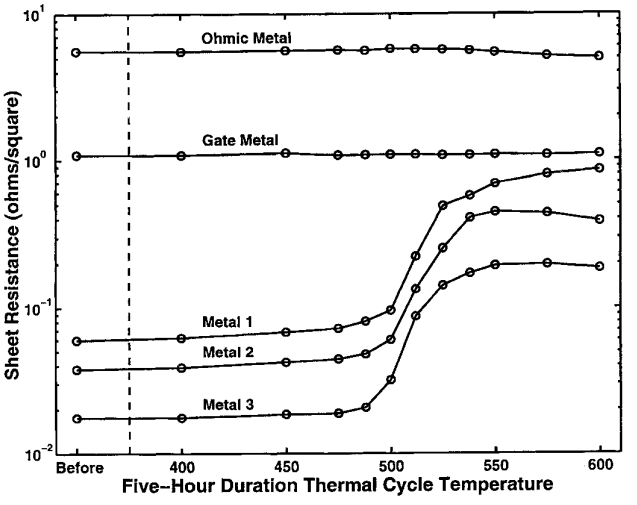

Fig. 1. Metal-layer sheet resistance after 5-h thermal cycles. The gate metal consists of 3500 Å WN_x deposited over the channel implant. The ohmic metal consists of 700 Å NiGe deposited over the source/drain (S/D) implant followed by a 1000 Å WN_x barrier. The metal 1 through metal 3 layers are a $Wn_x/AlCu_x/WN_x$ sandwich with thickness ranges of (1000 Å-1500 Å)/8000 Å-17000 Å)/(1000 Å), respectively. The WN_x contains 10–20 atomic percent nitrogen and the $AlCu_x$ contains about 1% copper.

III. Results and Discussion

Fig. 1 shows the gate metal, ohmic metal and interconnect metal 1 through 3 sheet resistances as a function of 5-h thermal cycle (FHTC) temperature. The gate and ohmic metal layers displayed almost no sheet resistance change even after

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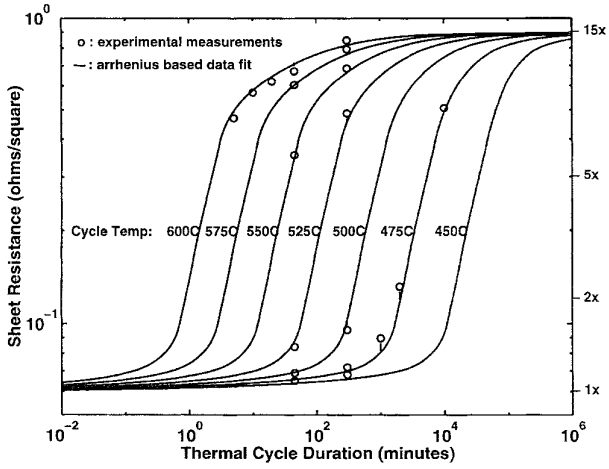
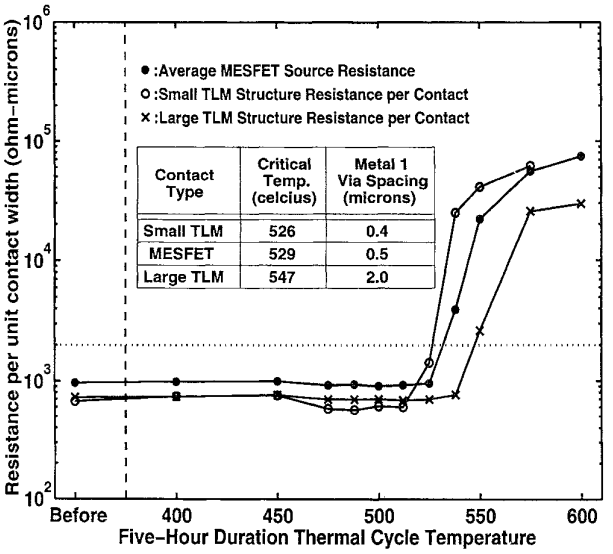


Fig. 2. Metal 1 sheet resistance thermal cycle response Arrhenius-based model and data measurements.



Contact Type	Critical Temp. (celcius)	Metal 1 Via Spacing (microns)
Small TLM	526	0.4
MESFET	529	0.5
Large TLM	547	2.0

Fig. 3. Average MESFET source resistance and large and small TLM resistance per unit contact width after 5-h thermal cycles. The inset table summarizes the 2000 ohm-micron critical temperature and metal 1 via spacing for each ohmic contact structure.

5 h at 600°C. This is a strong indication that there are no large scale metallurgical reactions between WN_x, NiGe, GaAs, and the SiO_2 passivation for up to 5 h at 600°C. However, the aluminum-containing metal 1 through 3 layers showed a striking sheet resistance increase after 5 h in the temperature range 400°C to 600°C. This resistance increase is believed to be the result of a metallurgical reaction between the $AlCu_x$ core and WN_x claddings,

$$AlCu_x + WN_x \rightarrow \text{Al-Cu-W-N (unknown proportions)}.$$

Reaction between Al and WN_x has been previously reported to occur at temperatures as low as 500°C [3] with reaction products including $Al_{12}W$ and AlN.

The metal 1 sheet resistance increased linearly in time with thermal activation energy 3.5 eV before saturating at approximately 15 times the before cycle sheet resistance. Using an Arrhenius based model, a curve set was fitted to the measurements to predict the metal 1 sheet resistance for arbitrary times in the temperature range 400°C to 600°C. Fig. 2 shows this model with excellent agreement to experimental measurements from five minutes at 600°C to one week at 475°C.

The thermal response of $WN_x/AlCu_x$ layers with increased nitrogen content WN_x was investigated by adjusting the tungsten sputtering rate with constant nitrogen flow rate. Layers deposited with the tungsten sputtering rate a factor of four slower than the normal process showed no sheet resistance increase even at 5 h at 550°C. This deposition modification is one possible way to improve the WN_x barrier.

The ohmic-contact resistance thermal cycle response was isolated through the measurement of metal 1-ohmic contact-S/D implant (M1-OM-N+) contact strings, metal 1-ohmic metal (M1-OM) contact strings and S/D implant resistors. The M1-OM-N+ resistance per contact was observed to increase following FHTC's at temperatures above 500°C. After 5 h at 550°C, the M1-OM-N+ resistance per contact increased from a before cycle value of 200 ohms per contact to over 10 000 ohms per contact. However, the M1-OM resistance per contact and the S/D implant sheet resistance showed no increase after FHTC's at temperatures up to 600°C. These observations clearly indicated that, after elevated temperature cycles, the increased M1-OM-N+ resistance per contact is the result of increased ohmic contact resistance.

All of the ohmic contact containing resistances exhibited common thermal cycle response features. The ohmic-contact resistance increase was delayed in time, thermally activated (E_a = 2.5 eV to 3.0 eV) and highly variable. However, the delay before the onset of ohmic-contact resistance increased was found to depend strongly on the ohmic-contact metal 1 via spacing, defined as the distance between the metal 1 via edge and the ohmic contact metal edge. This dependence is displayed in Fig. 3 which shows the average measured MESFET source resistance and the small and large TLM structure resistances per unit contact length as a function of FHTC temperature. The FHTC critical temperature was defined as the temperature where the resistance per unit contact length exceeded 2000 ohm-μm.

The strong correlation between the ohmic contact to metal 1 via spacing and the FHTC critical temperature is tabulated in the Fig. 3 inset and provides a basis for understanding the physical mechanism responsible for the ohmic contact resistance increase. It is proposed that the ohmic contact resistance increase is the result of a reaction between Al-Cu-W-N and Ni-Ge upon aluminum compound penetration through the WN_x barrier to the ohmic contact metal edge. Strain due to thermal-expansion mismatch between the ohmic metal and GaAs crystal is concentrated at the ohmic metal edge and is believed to provide a preferential site for new phase nucleation and growth [4]. The WN_x barrier to penetration to the ohmic metal edge consists of the metal 1 bottom cladding (1500 Å) plus the ohmic metal top layer (1000 Å) plus the via

spacing (4000 Å to 20,000 Å), thus explaining the correlation between ohmic-contact critical temperature and ohmic contact to metal 1 via spacing.

Six EFET's and three DFET's of varying gate width and length were measured before and after each thermal cycle. The Schottky gate contact was stable for all thermal cycles with ϕ_b and n showing no significant trends. However, MESFET transconductances and saturation currents decreased as the source and drain resistances increased. Following severe thermal cycles, such as 5 h at 550°C, the MESFET source resistance measurements over nine devices showed a coefficient of variation approaching unity in addition to a large average increase. The statistical spread in ohmic-contact resistance increase is believed to be the result of the nonuniform penetration of aluminum through the WN_x barrier [3]. HSPICE device simulations showed that the transconductance and saturation current decrease was accurately modeled by including resistors at the MESFET source and drain terminals equal to the measured source and drain resistance increases.

The oscillation period of the 23-stage DCFL ring oscillators was unaffected by thermal cycling after 5 h at up to 450°C. Following 5 h at 450°C to 540°C, the ring oscillator period was measured to increase by about 10%, but remained well within the before cycle delay distribution. However, no oscillations were observed after 5-h thermal cycles at 550°C and above. HSPICE simulations including the ohmic contact resistance increases at the MESFET source and drain terminals correctly predicted that ring oscillators would not function after 5-h thermal cycles above 540°C.

IV. Conclusion

At elevated temperatures, a metallurgical reaction, $AlCu_x + WN_x \rightarrow$ Al-Cu-W-N, occurs within the interconnect metal layers. This reaction proceeds linearly in time and with activation energy 3.5 eV until the system reaches a new equilibrium at 15 times the original sheet resistance. In addition, aluminum-containing reaction product penetration through the ohmic contact WN_x barrier to the edge of the ohmic metal results in dramatically increased contact resistance. The models developed for these processes suggest process and layout changes that can be expected to lead to improved device and circuit stability for high temperature operation and during epitaxial growth, and increased reliability at all temperatures.

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