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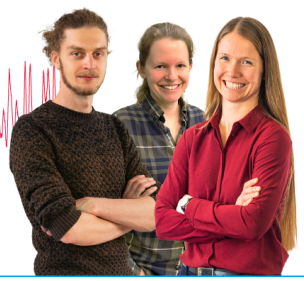

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ABSTRACT

This Letter reports the stability of regrown and alloyed Ohmic contacts to AlGaN/GaN-on-Si high electron mobility transistors (HEMTs) for high temperature applications up to 500 °C. Transfer length method (TLM) measurements from 25 to 500 °C in air show that the regrown contacts appear to be stable up to 500 °C during short term (approximately 1 h) testing, while alloyed contacts appear to decrease in contact resistance from 300 to 500 °C though increases in the error bounds due to increase sheet resistance make it difficult to conclude definitely. Additionally, longer term testing shows both technologies remain stable at least up to 48 h at 500 °C, after which the large increase in sheet resistance makes the measurement uncertainty too large to conclude definitively. Advanced microscopy images indicate both the regrown and alloyed contact regions remain structurally intact after prolonged high temperature exposure with no visible degradation in crystallinity or metal composition.

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Recent years have witnessed the emergence of many exciting applications of high temperature (HT) electronics, including those related to Venus exploration, hypersonic flight, jet engines, automotive vehicles, chemical plants, and geothermal energy.[1] These applications all require electronics capable of operating beyond the 250 °C temperature limit of standard silicon and silicon-on-insulator (SOI) technology. The low intrinsic carrier concentration of wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) at these high temperatures (>250 °C) makes these semiconductors ideal for these applications. GaN-based electronics is especially promising over SiC due to its higher mobility, larger critical electric field, and larger bandgap.[2,3] There have been many excellent demonstrations of HT GaN-based devices[4–13] and circuits[14–17] in the past decade. Moreover, significant progress has been made on understanding HT degradation in GaN-based HEMTs.[18–20]

Despite the great interest and progress in GaN-based HT electronics, the stability of regrown and alloyed Ohmic contacts to AlGaN/GaN HEMTs has not been extensively studied at high temperatures, with only a few works studying the reliability of Ohmic contacts at 400 °C or greater.[21–25] As GaN-based devices continue to scale to shorter channel dimensions, the Ohmic contacts begin to become a larger contribution of the total device resistance. For example, the

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contact resistance alone can contribute over 20% of the total device resistance for high performance GaN channel devices with dimensions of $L_{sd} < 1\,\mu m$.[26,27] Traditionally, AlGaN/GaN Ohmic contacts are formed by alloying a Ti/Al/Ni/Au based contact (or some variant thereof) through a rapid thermal anneal (RTA) process, typically around 700–900 °C for 30–60 s. More recently, regrown contacts, in which molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) is used to grow highly doped GaN to enable low contact resistance, have become the standard for state-of-the-art high frequency GaN HEMTs.[28,29] However, detailed investigations of the HT stability of regrown and alloyed Ohmic contacts to AlGaN/GaN HEMTs at 500 °C and above remain sorely lacking.

This Letter reports a holistic study of the impact of temperature on the contact resistance of both regrown and alloyed contacts, through (1) electrical characterization of regrown and alloyed contacts using transfer length method (TLM) structures across temperature on a hot chuck probe station in air for up to 1 h; (2) long-term temperature degradation studies of TLM structures up to 72 h at 500 °C; and (3) advanced microscopy of the aforementioned samples.

As is seen in Fig. 1, TLM structures with both regrown and alloyed contacts were fabricated on a standard AlGaN/GaN epitaxial structure (2 nm GaN cap, 17 nm $Al_{0.23}Ga_{0.77}N$ barrier, 1 nm AlN spacer (not shown), and 800 nm unintentionally doped GaN channel) grown by metal-organic chemical vapor deposition (MOCVD) on Si (111) substrate. The regrown n^{++} GaN was grown via MBE with a nominal silicon doping concentration of $\geq 1 \times 10^{20}\,cm^{-3}$ and thickness of ≈70 nm at a growth temperature of 750 °C (T_{sub}). Prior to regrowth, the sample was exposed to multiple cycles of Ga flux to remove any native suboxides from the GaN surface.[30] The angle of the regrown trench is approximately 58° as was measured through transmission electron microscopy images of the samples after the regrowth. On samples with regrown contacts, two types of TLMs were fabricated. Figure 1(a) shows TLMs with n^{++} GaN selectively regrown in only the contact regions as would be the case for a HEMT. Figure 1(b) shows TLMs on the same regrown sample with n^{++} GaN regrown in all of the contact and channel region. Following a similar procedure as is detailed in Ref. 31, utilizing both structures, the various contributions of the regrown contact resistance can be extracted, namely, (1) $R_{c,1}$: metal to n^{++} GaN contact resistance, (2) $R_{c,2}$: n^{++} GaN access resistance, and (3) $R_{c,3}$: n^{++} GaN to 2DEG interface resistance. A Ti/Al/Ni/Au (20/100/25/50 nm) metal stack was used for the Ohmic metal stack of all TLM structures to control for the contact metal resistance. In the case of the alloyed contacts, this metal stack is annealed at 825 °C for 30 s in N_2 ambient. After the mesa etch, 200 nm of additional pad metal was deposited to ensure repeatable electrical measurements. The details of the process flow for the regrown, and alloyed contacts are reported in the supplementary material secs. 1 and 2, respectively. The TLM structures are 25 μm wide with nominal TLM gap L = 2–20 μm in 2 μm increments. The Ohmic metal region of the TLMs for both the regrown and alloyed samples is 25 μm × 25 μm. The selectively regrown n^{++} area is 250 nm wider than the Ohmic metal region of the TLM.

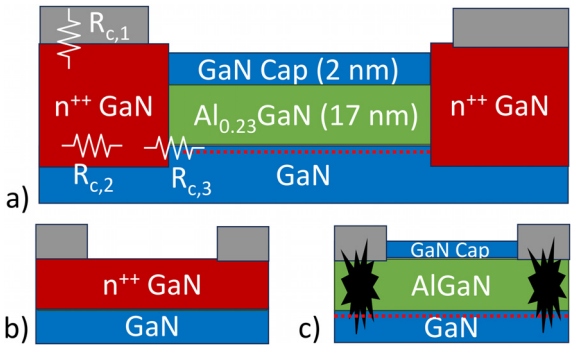

FIG. 1. Structures of AlGaN/GaN TLMs studied in this work. (a) Selectively regrown n^{++} ($[Si] \geq 1 \times 10^{20}\,cm^{-3}$) GaN contacts in the Ohmic region only with the different contributions of the contact resistances $R_{c,1}$, $R_{c,2}$, and $R_{c,3}$ labeled. (b) Regrown n^{++} GaN over entire TLM region. (c) Ti/Al/Ni/Au alloyed contacts.

For both the "selective" and "all" regrown [Figs. 1(a) and 1(b)] and alloyed TLM structures [Fig. 1(c)], four sets of TLMs were measured *in situ* using a four-point Kelvin probe technique on a hot chuck probe station from 25 to 500 °C in air. The selective regrown [Fig. 1(a)] and alloyed [Fig. 1(c)] TLM results are shown in Figs. 2(a) and 2(b), respectively. The all-regrown structures were also measured but have been omitted in Fig. 2 for conciseness (see supplementary material Sec. 3). The temperature ramp rate was approximately 10 °C/min, and at each temperature, the samples were held for 10 min to reach thermal equilibrium before beginning TLM measurements. At each temperature, the total duration of the TLM measurements was approximately 1 h. Figure 2(c) shows the extracted contact resistance for the selective regrown [Fig. 1(a)] and alloyed contact structures at each of the temperatures measured in Figs. 2(a) and 2(b) with error bars representing the 95% confidence interval of the linear fit to the TLM data. As the temperature increases, the sheet resistance of the AlGaN/GaN 2DEG channel increases substantially due to reduction of the channel mobility from increased polar optical phonon scattering as can be seen in the increasing slope of the TLM measurements with temperature in Figs. 2(a) and 2(b).[32]

Figure 2(c) shows the extracted contact resistances at each temperature with the error bars indicating the 95% confidence interval from the linear fit of data from all four TLM sets. The contact resistance of the regrown contacts [Fig. 1(a)] remains relatively constant throughout the temperature range of 25–500 °C. On the other hand, the alloyed contacts exhibit a slight decrease in contact resistance though it is difficult to definitively conclude this due to the large error bars at high temperatures as was also noted in Ref. 19. This is partially because the large sheet resistance leads to a large slope in the TLM fit, which then causes a relatively large uncertainty in the fit of the y-intercept, thus the contact resistance [Figs. 2(e) and 2(f)].[33] Similarly, this leads to falsely negative contact resistance values after the sheet resistance of the channel becomes too high at high temperatures as is seen by the large error bars for these R_c values.

As the contact resistance for both samples was relatively stable during short (approximately 1 h) measurements from 25 to 500 °C, pristine, sister samples as those measured on the hot chuck were used for long-term stability measurements. These samples were placed in a furnace at 500 °C in a N_2 environment as is described in Ref. 34. After regular intervals, the samples were removed from the furnace, and *ex situ* measurements were made at room temperature. As can be seen in Fig. 3(a), both the regrown [Fig. 1(a)] and alloyed contacts show good temperature stability up to a 24 h annealing period. Furthermore, from the contact resistance component breakdown of the regrown sample

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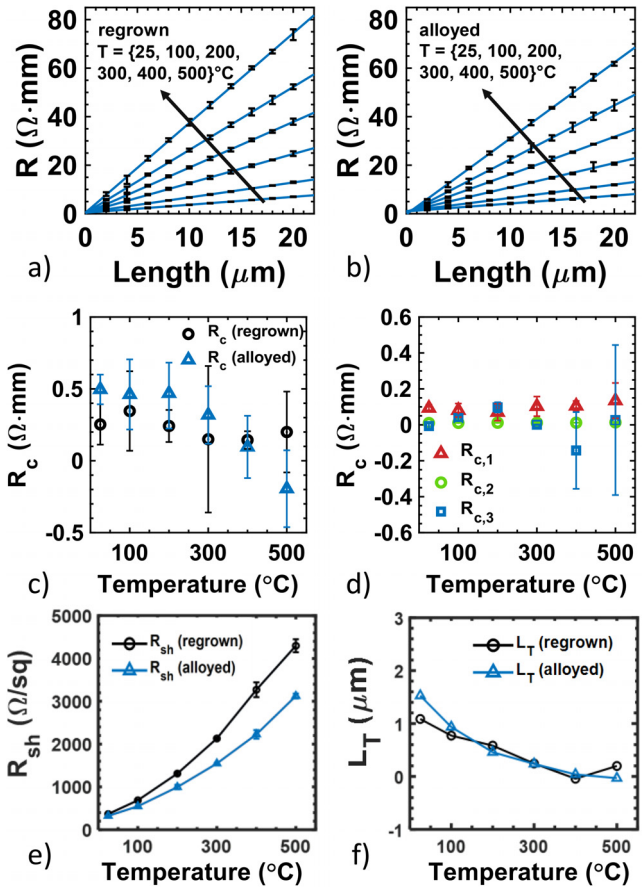

FIG. 2. *In situ* electrical measurements of TLM structures with L = 2–20 μm, ΔL = 2 μm, N = 4, from 25 to 500 °C on a hot chuck probe station in air for (a) selectively regrown structure TLMs and (b) alloyed contact TLMs described in Figs. 1(a) and 1(c), respectively. Average values are plotted with error bars representing one standard deviation. (c) Extracted average R_c vs temperature for the regrown and alloyed TLMs from (a) and (b). Error bars represented the 95% confidence interval from the linear fit. (d) Breakdown of the different contact resistance components vs temperature of the selective regrown TLM structures as indicated in Fig. 1(a). Extracted average R_{sh} vs temperature (e) and (f) L_T vs temperature for the regrowth and alloyed TLMs from (a) and (b).

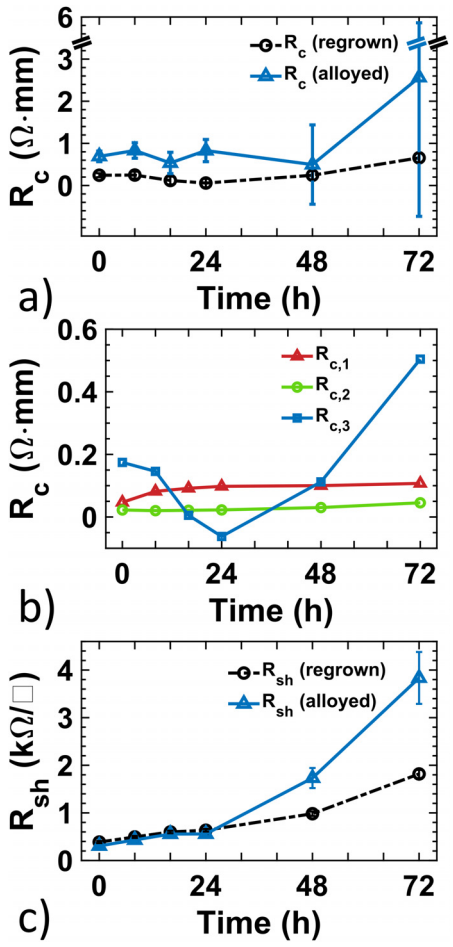

FIG. 3. *Ex situ* measurements made at room temperature (a) of contact resistance of a set of regrown TLMs and alloyed TLMs after repeated exposure to a 500 °C, N_2 environment over a 72 h period. (b) Breakdown of the different contact resistance components over the 72 h period of the regrowth TLM structures. (c) Sheet resistance extracted from the same TLM samples over the same period.

shown in Fig. 3(b), it can be seen that the $R_{c,1}$ and $R_{c,2}$ are relatively stable throughout the period, while $R_{c,3}$ appears to decrease and then increase. This indicates that the regrown n^{++} GaN regions are thermally stable; however, the interface between the 2DEG and regrown GaN appears to be impacted by the thermal exposure. This is likely due to degradation to the surface of the AlGaN barrier after prolonged HT exposure, which then depletes the 2DEG underneath it. As the contact resistance between the n^{++} GaN and 2DEG depends on the 2DEG density near the interface leading to both the observed fluctuations in $R_{c,3}$ and the rapid increase in R_{sh} after 48 h, as shown in Fig. 3(c). It should be noted that due to this rapid increase in R_{sh} after 48 h, the $R_{c,3}$ component that is extracted from TLMs with such large sheet resistance has a large uncertainty.

Atomic force microscopy measurements of the pristine and HT-exposed samples show that the root mean square (RMS) surface roughness increased from 1.05 to 2.19 nm, indicating there is a possibility that the AlGaN barrier has been impacted by the prolonged thermal exposure (see supplementary material section 4). This is consistent that the degradation of the AlGaN barrier is reducing the 2DEG density in the channel, which will directly reduce the contact resistance at the interface.[35,36]

The structural integrity of the contact regions is further confirmed in transmission electron microscopy (TEM)[37,38] images of the TLM samples before and after the full 72 h testing period as shown in Fig. 4, which are hereinafter referred to as the pristine and HT-exposed samples, respectively. A schematic is shown in Fig. 4(a) representing the interface of the AlGaN, GaN, and regrown GaN regions. Real space bright field TEM image of this three-way intersection is shown in Fig. 4(b) for the pristine sample. Fast Fourier Transforms (FFTs) of the AlGaN/GaN and GaN/regrown-GaN interfaces are shown in Figs. 4(c) and 4(d). As expected, these show that the AlGaN/GaN interface and GaN/regrown-GaN interfaces of the pristine sample

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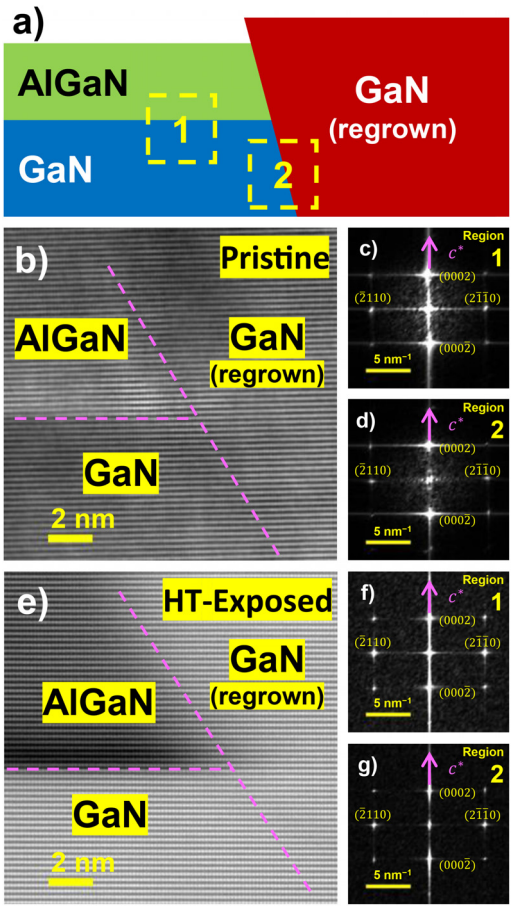

FIG. 4. TEM of the pristine and high temperature (HT) exposed (72 h at 500 °C in N_2 ambient) regrown contacts. (a) Schematic of interface between AlGaN, GaN, and regrown GaN region. Region 1 is the AlGaN/GaN interface, and region 2 is the GaN/regrown-GaN interface. (b) Bright field TEM image of pristine regrown contact with FFTs of regions 1 and 2 shown in (c) and (d), respectively. (e) Dark field STEM image of HT treated regrown contact with FFTs of regions 1 and 2 shown in (f) and (g), respectively.

have a high degree of crystallinity as exhibited by the highly localized peaks in the k-space. After the high temperature exposure, similar analysis was performed with a scanning transmission electron microscope (STEM) with the goal of obtaining higher resolution images to observe the degradation in interface quality. However, as is seen in the dark STEM images in Fig. 4(e), the HT-exposed sample still retains a high-quality interface between the regrown GaN and epitaxially grown GaN. This is further confirmed by the crystallinity observed in the FFTs of the interfaces as is seen in Figs. 4(f)–4(g). Note that the differences in brightness and contrast of the real space TEM images lead to differences in the brightness of the FFT patterns between the pristine and HT-exposed samples.

Similar to the regrown contacts, the alloyed contact region before and after prolonged HT appears to be stable according to TEM images (Fig. 5). Comparing the pristine and HT-exposed samples, there seems to be no noticeable difference in the metal contact morphology or elemental composition. Bright field TEM images of the alloyed contact region

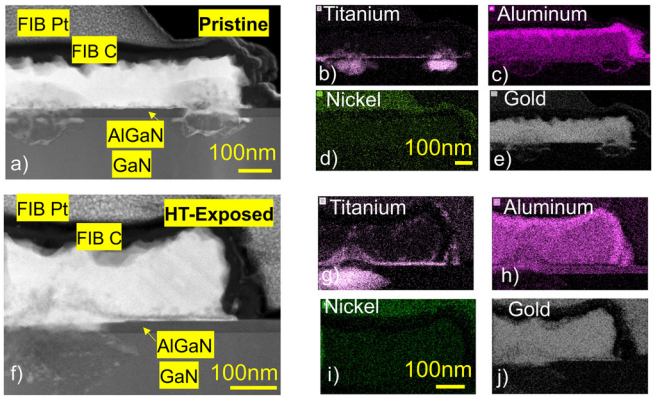

FIG. 5. TEM of the pristine and HT treated (72 h at 500 °C in N_2 ambient) alloyed contacts. (a) TEM image and (b)–(e) EDS elemental mappings of a pristine alloyed contact before any high temperature testing. (f) TEM image and (g)–(j) EDS element mapping of an alloyed contact TLM after 72 h at 500 °C. Note that scale bars between (a) vs (f), and (b)–(e) vs (g)–(j), are slightly different.

before and after HT exposure are shown in Figs. 5(a) and 5(f), respectively, with noticeable TiN alloy islands protruding into the AlGaN/GaN channel as is commonly reported in the literature.[39,40] Furthermore, energy-dispersive x-ray spectroscopy (EDS) results [Figs. 5(b)–5(e) and 5(g)–5(j)] show that elemental composition of the alloyed metal stack remains qualitatively the same before and after HT exposure.

In conclusion, this work studied the high temperature stability of regrown and alloyed contacts to AlGaN/GaN through electrical characterization of TLM structures and TEM. Hot chuck probe station measurements in open air show that the regrown contact remains stable up to 500 °C. Alloyed contacts appeared to have a slightly decrease in contact resistance after 400 °C. For both samples, at high temperatures, the large increase in sheet resistance led to large uncertainties in the contact resistance extraction. Prolonged HT (500 °C) exposure indicates the R_c remains relatively stable up to 48 h, after which the large increase in R_{sh} makes further conclusions on contact resistance marginal. Furthermore, for both regrown and alloyed contacts, TEM images of pristine and HT-exposed show no noticeable degradation in the crystallinity and metallization. These results indicate that both regrown and alloyed contacts remain structurally intact and are promising ohmic contact technologies for thermally hardened GaN transistors. This study helps pave the way for future high temperature electronic applications based on III-N technology.

See the supplementary material for more detailed information on the process flow of the TLM structures, additional electrical measurements, and additional AFM metrology done on the samples presented in this Letter.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

John Niroula and Qingyun Xie contributed equally to this work.

John Niroula: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Qingyun Xie:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Nitul S. Rajput:** Conceptualization (supporting); Formal analysis (supporting); Methodology (supporting); Visualization (supporting); Writing – review & editing (supporting). **Patrick K. Darmawi-Iskandar:** Formal analysis (supporting); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Sheikh Ifatur Rahman:** Data curation (supporting); Formal analysis (supporting); Writing – original draft (supporting). **Shisong Luo:** Data curation (supporting); Writing – original draft (supporting). **Rafid Hassan Palash:** Formal analysis (supporting); Visualization (supporting); Writing – original draft (supporting). **Bejoy Sikder:** Formal analysis (supporting); Visualization (supporting); Writing – original draft (supporting). **Mengyang Yuan:** Data curation (supporting); Writing – original draft (supporting). **Pradyot Yadav:** Data curation (supporting); Visualization (supporting); Writing – original draft (supporting). **Gillian K. Micale:** Data curation (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Nadim Chowdhury:** Supervision (supporting). **Yuji Zhao:** Supervision (supporting). **Siddharth Rajan:** Supervision (supporting). **Tomás Palacios:** Funding acquisition (lead); Project administration (lead); Resources (lead); Supervision (lead); Writing – original draft (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

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