Structural and electrical characterization of AuPtAlTi ohmic contacts to AlGaN/GaN with varying annealing temperature and Al content

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Abstract

The effect of varying annealing temperature and Al layer thickness on the structural and electrical characteristics of AuPtAlTi/AlGaN/GaN ohmic contact structures has been systematically investigated. The relationship between annealing temperature, Al content, interfacial microstructure, surface planarity and contact resistance is examined. In particular, the presence of a detrimental low temperature Pt-Al reaction is identified. This is implicated in both the requirement for a higher Al:Ti ratio than is required for related AuPdAlTi contact schemes and through the degraded temperature dependent resistance behaviour of the annealed AuPtAlTi contacts.

I. INTRODUCTION

AlGaN/GaN field effect transistors (FETs) are of commercial interest as a replacement for GaAs based devices, as high power, high frequency electronic device structures for microwave/radar applications. Military and commercial requirements for high power and high frequency amplifiers will continue to drive research aimed at producing further improvements in the performance of these devices. For example, the DARPA:MTO: Wide Band Gap Semiconductor Technology Initiative requires high efficiency devices operating over the 8-12 GHz range with >60% power added efficiency, high frequency devices operating at >40 GHz, and high bandwidth devices operating over the 2-20GHz range [1]. In particular, commercial communications are driving demand for higher output power amplifying devices to replace existing GaAs based FETs used in microwave base station, e.g. with the recent report of a GaN based FET with 174W output power at 6 GHz [2].

It is still not clear that contact technology is sufficiently robust to meet these very stringent demands. The specific issues concern contact planarity and the stability of ohmic contacts at elevated temperature. GaN-based FETs are intended to perform over higher operating temperature ranges than GaAs based FETs and it is therefore desirable to optimise contact performance over the range of 25-250°C.

The standard ohmic contact to n-type GaN and AlGaN is the Al/Ti diffusion couple [4-6]. Ohmic behaviour of this contact scheme is obtained after annealing, being related to the formation of a thin TiN or $AlTi_2N$ layer at the metal/contact interface. It is considered that the depletion of N from the nitride results in a strongly n-doped nitride surface layer and hence sufficient bending of the conduction band occurs to allow the tunnelling of carriers [4-9].

Diffusion couple multilayer contacts based on the Al/Ti scheme often employ Au as a non-oxidising, low resistivity coating to prevent the formation of highly resistive Ti and Al oxides [10]. There has been concern that Au can diffuse through the Al/Ti layers to the contact/nitride interface at high annealing temperatures [10], and hence barrier materials such as X = Ni, Ti, Pd, Pt or Mo have been introduced between the Au and Al/Ti layers to try to limit this effect [11-15]. It has been shown more recently that the presence of Au at the contact/AlGaN interface may not necessarily be detrimental to contact performance [16-20]. However, the presence of an Au/Al diffusion front has previously been observed at the boundary of TiN inclusions extending into the AlGaN layer within high temperature annealed metal diffusion couple contacted samples [18-19] and these have implication for the performance of these devices at elevated temperatures. For example, in the AuPdAlTi contact scheme, it has been observed that such ‘over-developed’ contacts (with TiN inclusions) show increasing resistance with increasing temperature, in contrast to ‘developed’ contacts (without TiN inclusion) which exhibit no strong relationship between temperature and contact resistance over the 25°C to 200°C range [18]

While it is known that AuXAlTi diffusion couple multilayers result in a lower contact resistance than conventional Al/Ti contacts [21-26], a full understanding of the controlling effect of the additional interlayers has not yet been achieved. The optimum Al/Ti ratio for ohmic contact formation to AlGaN/GaN FETs is known to be affected by the other elements present [16], whilst contact resistance development is further complicated by the additional variables of metal layer thickness, the Al content of the surface AlGaN layer, the pre-treatment of the nitride surface and the reproducibility of the annealing conditions applied. In order to separate out these differing effects, it is appropriate to consider the impact of such distinct variables on the performance of FET samples, as processed from a single wafer. In this work, a variety of complementary electron microscopy and electrical characterisation techniques have been used to investigate the effect of Al layer thickness and annealing temperature of the development of the contact/nitride interface within AuPtAlTi/AlGaN/GaN FETs, in order to show how the resultant microstructure relates to the contact electrical characteristics.

II. EXPERIMENT

AlGaN/GaN layers were grown on a conducting SiC substrate by metal organic chemical vapour deposition (MOCVD). After the deposition of AuPtAlTi contact metallisation schemes, the contacted samples were activated by rapid thermal annealing in flowing nitrogen, with a 5 minute purge at room temperature followed by a 30 second ramp to the annealing temperature, a 30 second hold at the annealing temperature, and a free cool to approximately 100°C before removal and subsequent air cooling.

For the purpose of this study, two sample sets were produced using distinct wafers. In the first case, ohmic contacts consisting of 50nm Au / 25 nm Pt / 50nm Al / 10nm Ti were processed and isolated by cleaving into sections for rapid thermal annealing at varying temperatures from unannealed to 950°C. Room-temperature Transmission Line Method (TLM) measurements were performed on this sample set. A second sample set was prepared for rapid thermal annealing at 850°C, with contacts consisting of 50nm Au / 25nm Pt / x nm Al / 10nm Ti, with x corresponding to 5, 10, 25 or 50nm.

Cross-sectional specimens for transmission electron microscopy (TEM) were prepared from the isolated contact pads by sequential mechanical polishing and dimpling, followed by argon ion milling to electron transparency. Liquid nitrogen cooling was used during the milling process to avoid further annealing of the samples. Specimens were examined using a JEOL 2000fx transmission electron microscope operating at 200kV, equipped with an Oxford Instruments ISIS system for conventional imaging and energy dispersive X-ray (EDX) analysis. A JEOL JEM 4000fx operating at 400kV, equipped with a Gatan Imaging Filter was used for high resolution imaging and Energy Filtered TEM (EFTEM) analysis.

Scanning electron microscopy (SEM) investigation of the contact pads was performed using an FEI XL30 FEG-ESEM. Peak to peak surface roughness of the annealed samples was measured using a DEKTAK stylus profilometer.

Subsequent to microstructural analysis, two samples typical of ‘developed’ and ‘over-developed’ contact schemes were selected for TLM analysis over a temperature range of 25-250°C.

III. RESULTS AND DISCUSSION

Room temperature TLM contact resistance measurements and peak to peak roughness values for the 50:25:50:10nm AuPtAlTi/AlGaN/GaN sample set as a function of annealing temperature are presented in Table I. An annealing temperature of at least 650°C was found necessary for the development of a reasonable ohmic resistance, with rapid thermal annealing at 800-850°C, in this instance, being associated with the lowest contact resistance values. However, it is noted that the surface roughness of the contacts increased markedly at anneals of 850°C or higher, i.e. with roughness values of 57nm at 800°C as compared with 206nm at 850°C.

Backscattered electron images of the unannealed 50:25:50:10 nm AuPtAlTi contacts in plan view and contacts annealed at 800°C and 900°C are compared in Figure 1. A significant increase in grain size and extensive chemical segregation with increasing annealing temperature was observed. EDX spot analysis of the grains indicated a significant separation of Au and Pt in the sample annealed at 900°C, with the regions showing up as dark in the backscattered electron images being largely Pt free. Conversely, light regions were found to be rich in Pt, whilst exhibiting a significantly lower Au content. The higher levels of Ga detected through the darker regions of this annealed contact layer are also indicative of significantly thinner regions of contact material, being consistent with increased roughening of the sample.

Bright field cross-sectional TEM images prepared from as-deposited 50:25:X:10 nm AuPtAlTi contacted samples show that the Al/Ti and Au/Pt interfaces remain clearly visible, but the Pt/Al interface is unclear, as shown in figure 2. In this instance, metal deposition occurred some months prior to preparation of the TEM samples. In this context, the reports of a low-temperature solid-state reaction between Pt and Al is noted [27-29].

A significant change in the integrity of the contact/nitride interface microstructure was observed for samples annealed at temperatures at or below 800°C, as compared with those annealed at or above 850°C (Figure 3). AuPtAlTi contacted samples annealed in the temperature range of 650°C to 800°C showed an abrupt interface between the contact and the AlGaN layer, marked by a thin interfacial layer some 10nm thick (Figure 3a, arrowed). However, with such annealing conditions, no penetration of material further into the AlGaN/GaN was observed. In comparison, Figure 3b shows an ‘over-developed’ interface typical of AuPtAlTi (50:25:50:10nm in this instance) contacts annealed at 850°C or higher. A thin interfacial layer was again observed in these samples (arrowed), in addition to inclusions penetrating through the AlGaN layer into the GaN below.

Elementally sensitive EFTEM images of a 50:25:50:10nm AuPtAlTi/AlGaN/GaN sample annealed at 700°C are presented in Figure 4. These chemical maps indicate that the contact/nitride interfacial layer is rich in both Ti and N, consistent with the expected interfacial Ti-nitride layer and the activation of contact ohmic behaviour with annealing. Further elementally sensitive images of the 10:50:25:50 sample, annealed at 850°C (Figure 5) indicate that Au has diffused to the contact nitride interface in this instance, and that the extending inclusions into the AlGaN are rich in Ti, deficient in Ga, whilst showing no reduction in N content, suggesting they are also a Ti-nitride phase, consistent with previous reports [17,18].

EDX line profiles across cross-sections prepared from as-deposited 50:25:x:10 nm AuPtAlTi contacted samples indicated that the original layered structure of the contact had already experienced some intermixing. Profiles from a 50:25:25:10 nm layer are

shown in Figure 6, in particular the Pt/Al interface is ill-defined with Pt being detectable at a position that should correspond to the centre of the intended layer.
Room temperature TLM measurements and peak to peak roughness for the AuPtAlTi sample with varying Al thickness are summarised in Table II. The lowest contact resistance results were achieved with an Al layer thickness of 50nm, giving an Al:Ti ratio of 5. This is similar to the Al:Ti ratio recommended for the related AuPdAlTi and AuNiAlTi schemes for contacted to AlGaN[18,30].

The formation of Ti-nitride inclusions and the rapid development of surface roughness are found to be strongly associated, with 50:25:20:10 AuPtAlTi samples annealed at 850°C showing inclusions and a significant increase in surface roughness, as compared with samples annealed at 800°C, in which no inclusions were observed. It is suggested that this is due to molten Al promoting the development of roughness, whilst freeing up Au to diffuse to the contact nitride interface, mediating the formation of inclusions.

TLM measurements obtained over a range of temperatures for two 10:50:25:50 AuPtAlTi samples, annealed at 800 and 850°C, respectively representing a ‘developed’ and ‘over-developed’ contact structure, are presented in Figure 7a. No clear difference in the electrical performance of these samples can be observed, despite marked differences in the contact nitride interfacial microstructures, with inclusions being present only in the sample annealed at 850°C. This is in contrast to the previous report on the related AuPdAlTi contact scheme where samples without inclusions were found to be superior to contacts with inclusions at elevated temperatures (Figure 7b) [18]. It is suggested that low temperature Pt-Al reaction may be implicated in this finding; however the exact mechanism responsible is as yet unclear. However, the suggestion is that it acts to reduce the amount of Al available for reaction with the Ti-layer at higher temperatures. The importance of this Pt-Al reaction controlling the development and performance of AuPtAlTi contacts at elevated temperatures is reinforced by report of a contact resistance for AuPdAlTi as low as 0.18±0.06Ohm.mm achieved by ensuring the alloying and hence contact activation occurs immediately following evaporation of the metal layers [31].

IV. CONCLUSION

All annealed AuPtAlTi contacted samples that show ohmic behaviour exhibit a Ti-rich layer at the contact/AlGaN interface. Ti-rich inclusions penetrating through the AlGaN layer were observed for annealing temperatures of 850°C or higher. This corresponds to a marked increase in the peak-to-peak roughness of these contacts, with molten Al allowing for the diffusion of Au to the contact nitride interface, hence linking inclusion formation into the AlGaN surface with the development of roughness. These results suggest an anneal of 800°C for AuPtAlTi contacts in terms of both contact resistance and surface planarity immediately following metal layer deposition is required for optimisation of the contact resistance.

Acknowledgements

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Table I. Contact resistance and peak to peak roughness of 50:25:50:10 nm AuPtAlTi/AlGaN contacts as a function of annealing temperature

Sample	Annealing Temp	Peak to peak roughness nm	Contact resistance Ω-mm
A	None	20.5	54.43±1.17
B	650°C	76.2	2.85±0.24
C	700°C	77.9	2.42±0.16
D	750°C	56.8	2.11±0.11
E	800°C	57.0	1.73±0.12
F	850°C	205.8	1.76±0.49
G	900°C	203.4	1.82±0.15

Table II. Contact resistance and peak to peak roughness of AuPtAlTi/AlGaN contacts with varying Al thickness

Sample	Al thickness (nm)	Peak to peak roughness nm	Contact resistance Ω-mm
5	5nm	4.5	44.9±4.8
10	10nm	70	43.2±1.7
25	25nm	75	12.4±2.1
50	50nm	45	0.7±0.9

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Figure 1: Plan view backscattered electron images 50nm Au / 25 nm Pt / 50nm Al / 10nm Ti contact pads (a) unannealed, (b) annealed at 800°C and (c) annealed at 900°C, showing the development of compositional segregation due to the diffusion of molten Al

Figure 2: Bright Field TEM image of an unannealed 50:25:50:10 nm AuPtAlTi/AlGaN/GaN layer. The Al/Ti and Au/Pt interfaces remain clearly defined, the Pt/Al interface cannot be discerned.

Figure 3: Bright-field TEM images of the 50:25:50:10 nm AuPtAlTi/AlGaN/GaN interface corresponding to annealing conditions of (a) 700°C and b) 850°C, respectively

Figure 4 Elementally sensitive images derived from an energy filtered TEM series of a 50:25:50:10 nm AuPtAlTi /AlGaN epilayer rapid thermally annealed at 700°C.

Figure 5: Elementally sensitive images derived from an energy filtered TEM series of a 50/25/50/10 nm AuPtAlTi/AlGaN epilayer after an 850°C RTA. Displacement of AlGaN/GaN by a Ti-nitride inclusion is indicated.

Figure 6 (Color online): Elementally sensitive line profiles derived from EDX spot spectra of an as-deposited 50nm Au / 25nm Pt / 25 nm Al / 10nm Ti ohmic contact to AlGaN. The Pt signal is affected by overlap with peaks due to the presence of Au. However, the presence of Pt closer to the AlGaN interface than would be expected from the as-deposited contact scheme is indicated (arrowed), consistent with the occurrence of a solid-state Pt-Al reaction.

Figure 7: (Color online) TLM contact resistance measured at varying temperature for a) 50:25:50:10 nm AuPtAlTi samples annealed at 800°C (showing no inclusions) and 850°C (showing inclusions), respectively, and b) 100 / 100/ 160 / x nm AuPdAlTi contacts with 30nm of Ti (showing no inclusions) and 160nm of Ti (showing inclusions).

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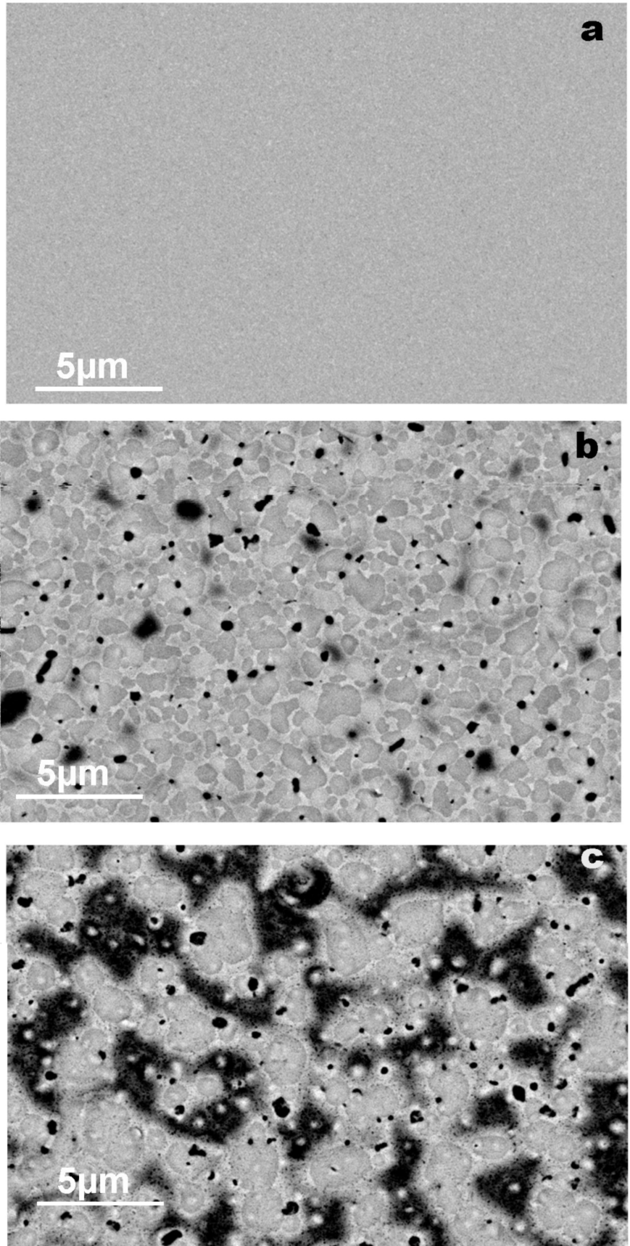

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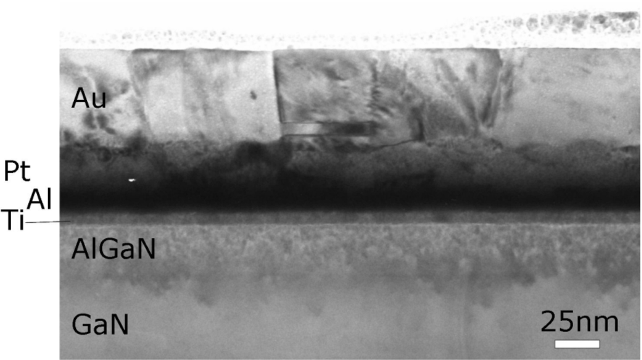

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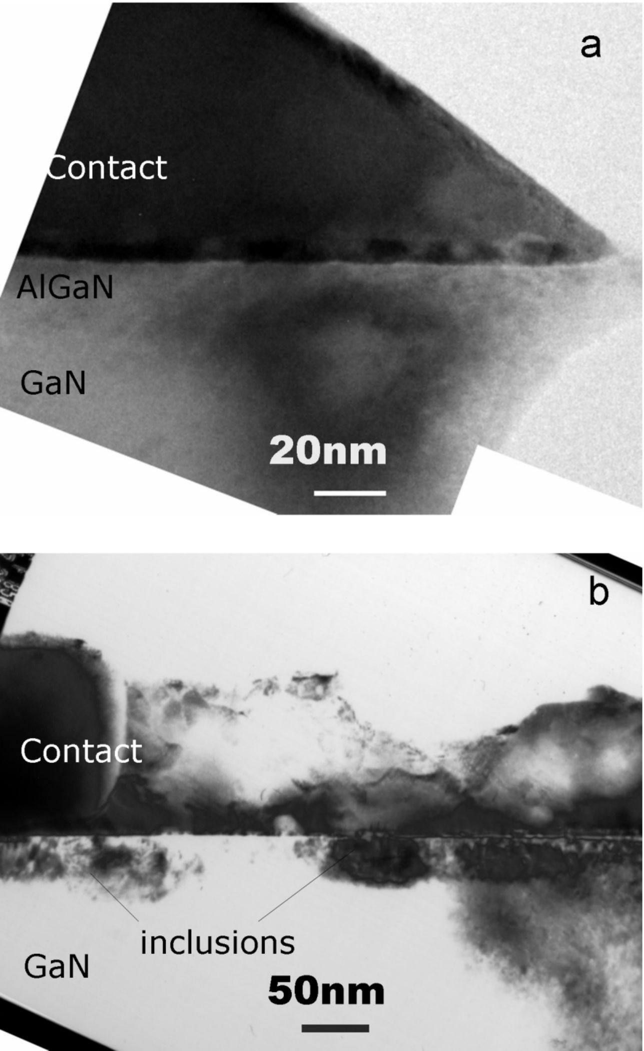

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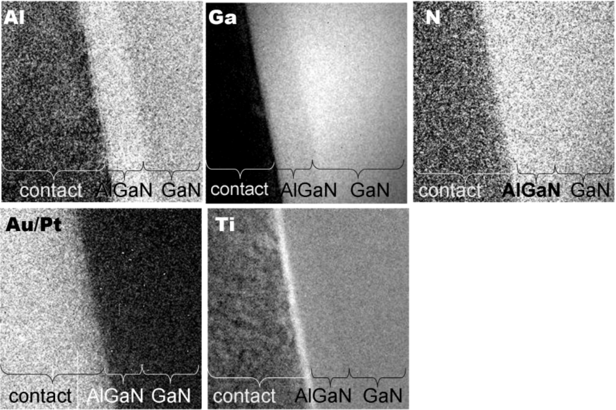
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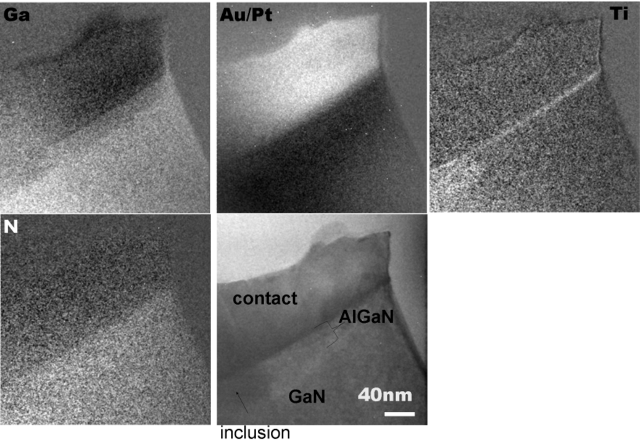

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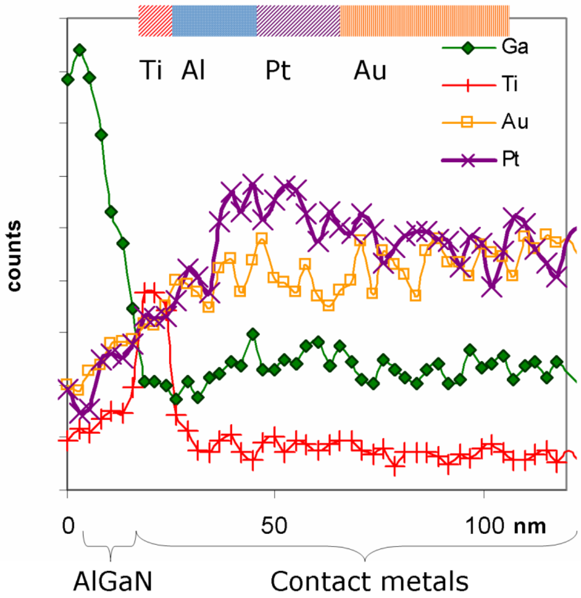

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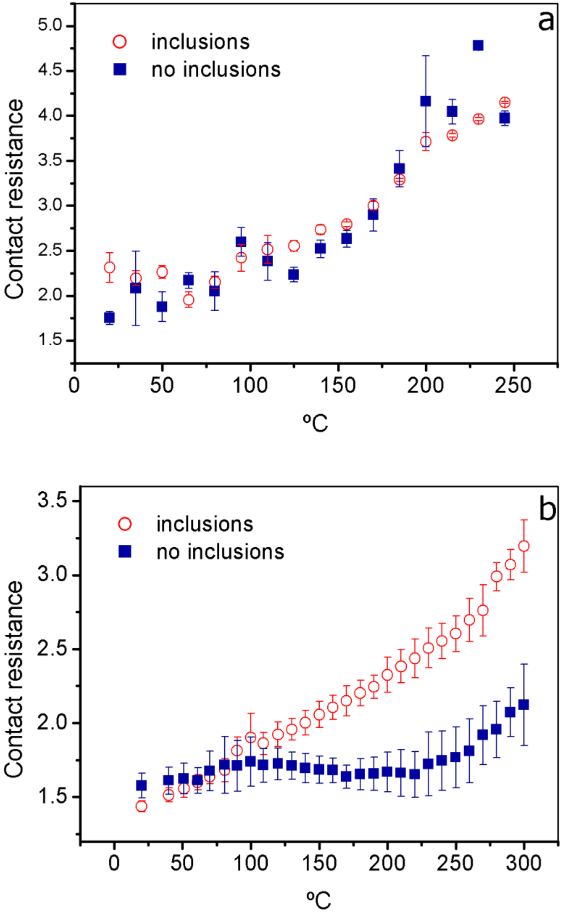
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