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Ohmic contacts on p-GaN (Part I): investigation of different contact metals and their thermal treatment

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Abstract

The changes in contact resistivity and $I-V$ curve linearity after annealing of Pd, Ni/Au, Cr/Au, Co/Au, Pt and Au contacts on p-GaN after tempering below and above 500°C have been investigated. CTLM-layered structures on p-GaN were thermally stressed and electrically analyzed. The $I-V$ curve linearity as a measure of ohmic behavior has been derived from the correlation coefficient of the $I-V$ curves. Below 500°C the Pd, Ni/Au, Cr/Au and Co/Au contacts become ohmic after annealing. The best final values of the specific contact resistance ρ_c after annealing increase in the sequence Ni/Au, Pd, Co/Au, Cr/Au, Au and Pt. After annealing above 500°C the contact resistance increases for all contact materials and the linearity decreases. A competition between the formation of reaction phases at the interface and the decomposition of the p-GaN epi-layer is a probable reason for this behavior.

1. Introduction

The development of high-power GaN laser diodes is one of the major challenges for the researchers currently working with light-emitting semiconductor materials. One of the major drawbacks is the lack of a low-resistance ohmic contact material on p-GaN. Favorable values for a low contact resistance are below $10^{-4}\,\Omega\,\text{cm}^2$. Although values down to $1.5\times10^{-3}\,\Omega\,\text{cm}^2$ have been reported [1], no verification by other researchers has taken place yet. The major problem impeding low-resistance ohmic contacts on p-GaN is the small carrier density of the Mg-doped p-GaN. The Mg doping concentration is generally about $10^{20}\,\text{cm}^{-3}$, but only 0.1–1% of the Mg atoms are activated, which leads to carrier densities around $p\sim5\times10^{17}\,\text{cm}^{-3}$.

The resistance of an ohmic contact on a specific semiconductor is determined by four major factors:

- The fabrication of semiconductor itself (here the p-GaN epi-layer).
- The preparation technique of the contact structure prior to contact deposition. This is mainly the treatment of the semiconductor surface.
- The choice of the contact materials and their deposition.
- The treatment of this contact by thermal annealing.

The choice of the contact material is usually connected directly with the choice of the annealing method, because only a few contact materials show ohmic behavior without thermal treatment.

The choice of contact materials on n-GaN as well as the treatment of the contact structures by annealing has been discussed in many papers (see [2] for an overview). Most of the researchers try this option first, because the choice of a fitting contact material gives a good starting point for further fine tuning of the contact properties. In contrast to n-GaN, not much has been published on ohmic contacts on p-GaN. Table 1 gives a short overview of the data available in the literature.

The impact of different contact metals and thermal treatments on the electrical properties of ohmic contacts on p-GaN will be investigated in this paper. A companion paper will focus on the impact of semiconductor fabrication and surface treatment [3].

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Table 1
Overview of published data on p-GaN/metal contacts

Metals	p-carrier density (cm^{-3})	Procedure	Spec. contact resistance, ρ_c ($\Omega\,\text{cm}^2$)	Author
Cr/Au	1.4×10^{20}	1 min at 500°C	3.0×10^{-4}	[1]
Pt/Au	1.4×10^{20}	1 min, temperature not specified	2.0×10^{-3}	[1]
Ti/Pt/Au	1.4×10^{20}	1 min, temperature not specified	6.0×10^{-4}	[1]
Pt/Au	6.0×10^{16}	10 min at 750°C	1.5×10^{-3}	[9]
Ni/Au–Zn	4.4×10^{17}	2 min, 600°C	3.6×10^{-3}	[12]
Ni/Au	10^{17}–10^{18}	500°C, time not specified	10^{-2}	[13]
Ni/Si	3.0×10^{17}	30 min at 400°C	1.0×10^{-2}	[14]
Ni/Cr/Au	1.0×10^{17}	30 s at 500°C	8.3×10^{-2}	[15]
Pd/Au	9.1×10^{16}	30 s at 500°C	9.1×10^{-3}	[16]
Cr/Au	9.8×10^{16}	15 s at 900°C	4.3×10^{-1}	[17]
WSi	1.0×10^{18}	300°C, no time specified	6.8×10^{-2}	[18]

2. Experimental

Layered contact structures on p-GaN were thermally stressed and electrically analyzed. The semiconductor material was Mg-doped p-GaN, grown on sapphire by MBE. The activated doping concentration was $p = 3 \times 10^{17}\,\text{cm}^{-3}$, measured by Hall effect.

For the contact experiments, pieces of about $10\,\text{mm}^2$ size were cut out of the GaN wafer. The surface treatment comprised a 30 s dip in acetone, 10 min in 40% HF and a final 30 s rinse in isopropanol. For further handling, the GaN pieces were mounted on a $1\,\text{cm}^2$ glass plate.

The CTLM structure was prepared by photolithography, four of the ring structures shown in Fig. 1 were deposited on each sample. The gaps between the CTLM contact rings are 30, 41, 51, 64 and 78 μm, respectively. The preparation included spin-coating with photoresistive, a soft-bake of the photoresistive for 1 min, exposition, development in an aqueous developer and a hard-bake for 5 min. The hard-bake step was omitted in some later experiments without any noticeable influence on the resulting electrical properties. The contact materials as well as a gold capping layer were dc-sputter deposited on the photolithographically prepared structure and a liftoff was performed. The layer thickness was about 100 nm for the contact metal and about 30 nm for the gold. The gold layer has been deposited to prevent the oxidation of the metal contact in air. Preliminary experiments without gold caps showed problems in reproducibly probing the contacts for Ni, Co and Cr. The gold capping was omitted on Pd, Pt and Au contacts.

The contacts were annealed in a flowing 93.5% Ar + 6.5% H_2-atmosphere under 1 bar. The annealing times varied between 30 s and 85 min for the different samples. Before annealing and after each annealing step the electrical properties were measured using a source measure unit (Keithley SMU236) and tungsten probes. The scheme used for the measurement of the electrical properties is shown in Fig. 2.

The $I-V$ data for the measurements #1, #2, #3 were determined for a voltage range 5–5 V. The three-point $I-V$ measurement #4, required to determine the specific contact resistance, has been done between −0.5 V and 0.5 V.

The data obtained by the measurements #1, #2 and #3 (see Fig. 3 as an example) were evaluated for each of the four ring structures on each sample. The inverse slope of the linear regression line of the $I-V$ curve (R) and the square of the correlation coefficient of the $I-V$ curves (r^2) were determined. The R-values for the annealed samples are given relative to the start value at 0 min

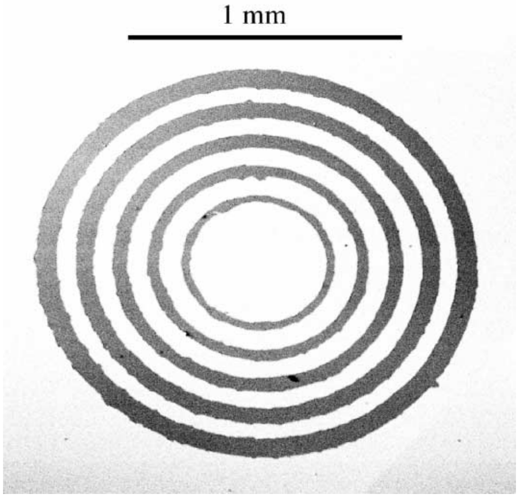

Fig. 1. SEM picture of the used CTLM structure; each sample included four of these rings (bright = metal layer).

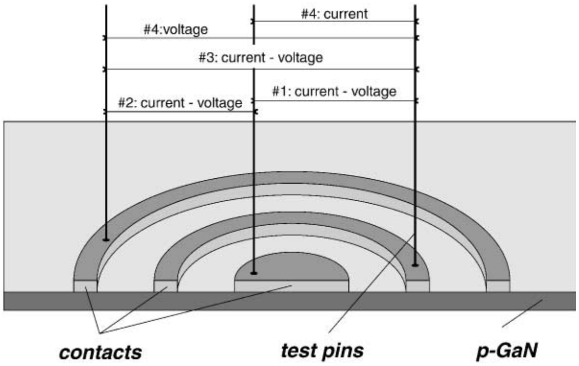

Fig. 2. Scheme of the measurement for determination of electrical properties using the CTLM structure.

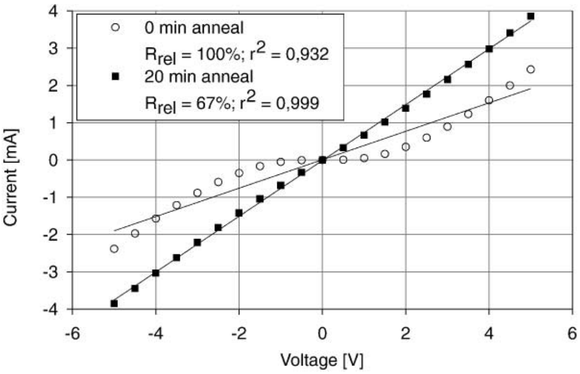

Fig. 3. $I-V$ curves for a p-GaN/Ni/Au contact before and after 20 min annealing at 430°C.

annealing time (R_0), which was set to 100%. Fig. 3 shows an $I-V$ curve for a sample before and after annealing, the values for $R_{rel} = R/R_0$ and r^2 are given. R/R_0 has been calculated for each of the 12 $I-V$ curves measured for each sample. The 12 values have been averaged to one value R_{rel}. The total mean error for all R_{rel} values shown in this paper is about 7%, the maximum error of 17% was observed for one single data point (p-GaN/Ni/Au, 10 min at 400°C). The error of r^2 is below 1% within each individual sample for all analyzed $I-V$ curves.

Both R_{rel} and r^2 were used to quantitatively describe the changing contact behavior with annealing. The relative values, R_{rel}, were used to determine more clearly the change caused by annealing and to exclude the initial scatter of absolute R_0 values observed on different samples. The correlation coefficient, r^2, quantifies the linearity of the $I-V$ curve, which would be $r^2 = 1$ for an ideal ohmic contact.

Data for the specific contact resistance (ρ_c), the semiconductor sheet resistance (R_s) and the contact end resistance (R_e) have been calculated from the separate measurement (#4) between 0.5 and −0.5 V using the procedure described in [4]. It should be noted, that ρ_c, R_s and R_e have only been measured if the contact has been ohmic. A threshold for a contact to be considered "ohmic" has been set to $r^2 > 0.990$ in this study. This is another reason why R_{rel} and not ρ_c has been used to characterize the response of contact structures to tempering. Although R_{rel} contains in principle the contact resistance (twice) plus the semiconductor sheet resistance, it is available in all cases. The lowest value for the specific contact resistance ρ_c is also reported for each metal/GaN combination.

3. Results

3.1. Palladium

The $I-V$ characteristics of p-GaN/Pd contacts have been investigated at 150, 300, 450 and at 600°C. The relative change of resistance R_{rel} is shown in Fig. 4, the correlation coefficient expressing the linearity of the individual $I-V$ curves is shown in Fig. 5. The dotted gray line in Fig. 5 represents the threshold of $r^2 > 0.99$, which has been set arbitrarily in this study to distinguish between ohmic and non-ohmic contact behavior.

At 150°C the resistance drops by about 15%, the decrease essentially occurs after 7.5 min. Further annealing for 12.5 min (20 min cumulated time) changes the resistance only within a few percent. This behavior applies also to the samples annealed at 300 and 450°C. The times needed to reach a static value are 20 min for 300°C and 5 min for 450°C. The sequence of the final values for R_{rel} are $R_{rel}(150°C) > R_{rel}(300°C) > R_{rel}(450°C)$. The resistance of palladium contacts on p-GaN decreases very fast during annealing at 600°C, after 1.5 min the lowest value is reached. After subsequent annealing R_{rel} increases by more than ten times

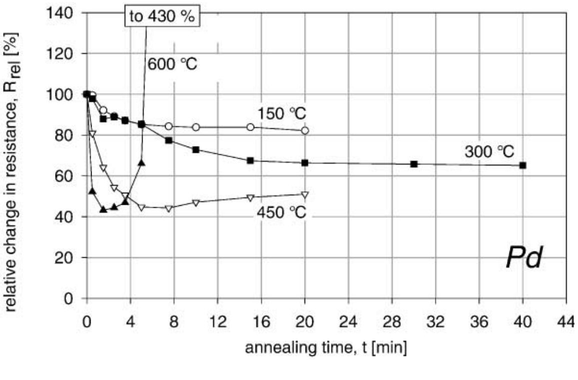

Fig. 4. Relative change of resistance versus cumulated annealing time for p-GaN/Pd contacts.

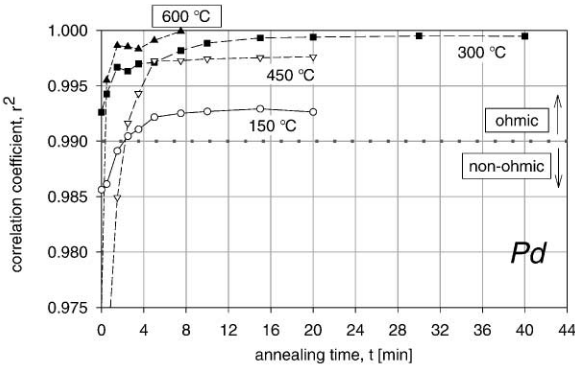

Fig. 5. Correlation coefficient versus cumulated annealing time for p-GaN/Pd contacts.

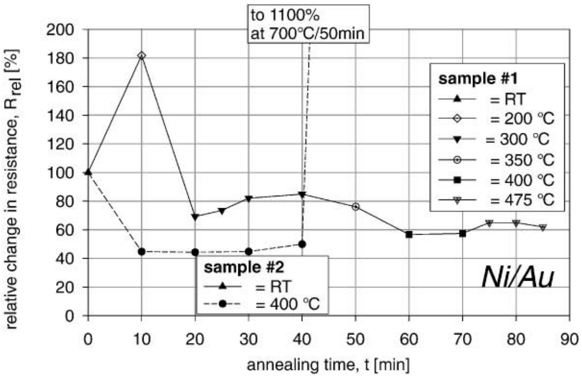

Fig. 6. Relative change of resistance versus cumulated annealing time for p-GaN/Ni/Au contacts (sample #1 lower curve, sample #2 upper curve).

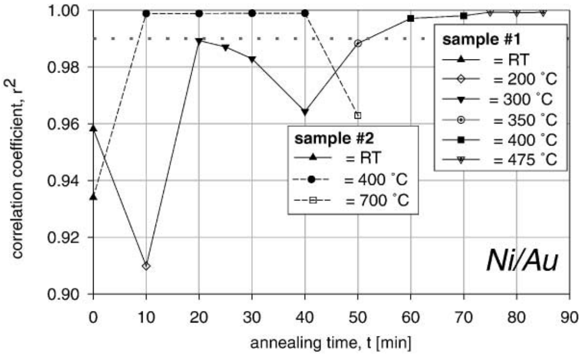

Fig. 7. Correlation coefficient versus cumulated annealing time for p-GaN/Ni/Au contacts (sample #1 upper curve, sample #2 lower curve).

($t = 7.5$ min), the contact surface appears black in an optical microscope.

The trend of r^2 as a measure for the ohmic behavior of the contact material correlates to the trend of R_{rel}. The times after which a static value is reached, are comparable for 150, 300 and 450°C. The contacts annealed at 600°C improve further although the resistance R_{rel} increases to 430%. The sequence of the final values of r^2 is $r^2(150°\mathrm{C}) < r^2(450°\mathrm{C}) < r^2(300°\mathrm{C}) < r^2(600°\mathrm{C})$.

The lowest specific contact resistance of $\rho_c = 0.2\ \Omega\,\mathrm{cm}^2$ has been measured after an anneal at 450°C for 7.5 min, this coincides with the minimum in R_{rel}.

3.2. Nickel/gold

The $I-V$ characteristics of p-GaN/Ni/Au contacts have been investigated in one series by progressively increasing temperature to 200, 300, 350, 400 and 475°C with a total annealing time of 85 min. Another series was done by isothermal annealing at 400°C up to 40 min, followed by a 10 min anneal at 700°C. The results for relative change of resistance R_{rel} are shown in Fig. 6, the correlation coefficients of the $I-V$ curves are shown in Fig. 7.

The resistance of sample #1 almost doubles its initial value after the first anneal at 200°C. The resistance decreases after the additional 10 min at 300°C to 70%, then R_{rel} fluctuates within 14%, twice the mean error of 7% during the following anneals at 350, 400 and 475°C. Resistance of sample #2 drops to 44% after the first anneal at 430°C/10 min, subsequent annealing up to 40 min increases the value slightly. The final anneal at 700°C raises the resistance up to almost 1100%, the contact surface looks dark in the optical microscope.

The correlation coefficient of sample #1 drops after annealing at 200°C from 0.958 to 0.909 (very non-linear $I-V$ curve), the next annealing step at 300°C raises the value back to 0.989. Further annealing reduces the value again, this is consistent with the slight increase of R_{rel} (see Fig. 6). The anneal at 350°C passes the threshold to an ohmic contact, the linearity improves further with the three annealing steps at 475°C.

The correlation coefficient r^2 of sample #2 after 400°C/10 min is comparable to r^2 of sample #1 after the anneal at 475°C. After a 10 min anneal at 700°C, r^2 drops back to 0.96 as R_{rel} increases to about 1100%. The lowest specific contact resistance has been measured for an additional sample annealed at 450°C for 15 min, the value is $0.1\ \Omega\,\mathrm{cm}^2$.

3.3. Chromium/gold

The $I-V$ characteristics of p-GaN/Cr/Au contacts have been investigated by isothermal tempering at 300, 350, 400 and 450°C. The relative change of resistance R_{rel} is shown in Fig. 8.

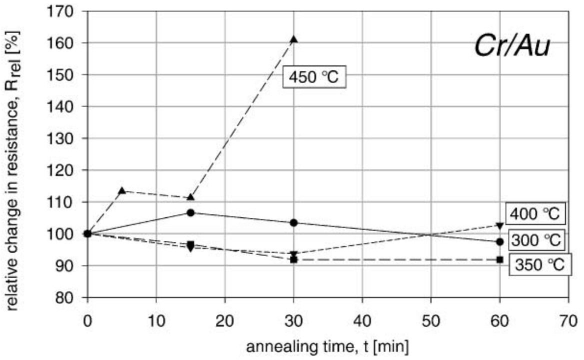

Fig. 8. Relative change of resistance versus cumulated annealing time for p-GaN/Cr/Au contacts.

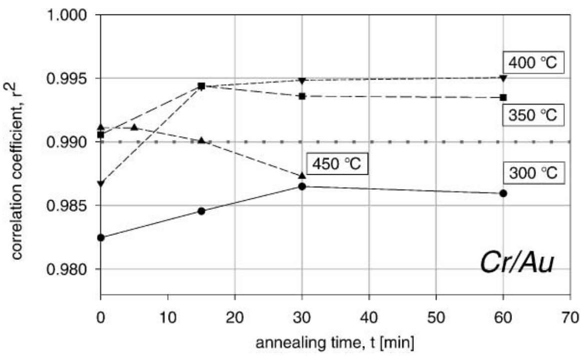

Fig. 9. Correlation coefficient versus cumulated annealing time for p-GaN/Cr/Au contacts.

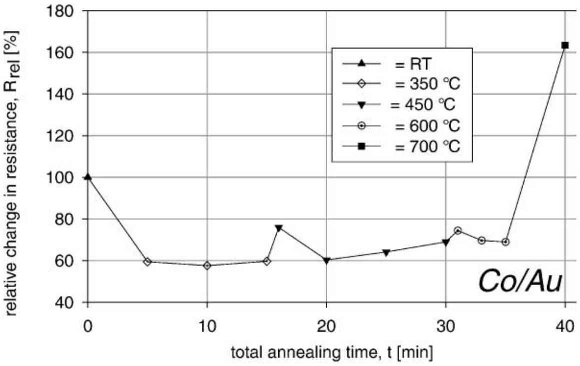

Fig. 10. Relative change of resistance versus cumulated annealing time for p-GaN/Co/Au contacts.

The change in resistance is small for the 300, 350 and 400°C samples, after 1 h annealing the R_{rel} values change within 92% (350°C) and 108% (400°C). The changes of R_{rel} are within the range of the mean error (±11%) determined from the 36 measurements. R_{rel} increases more rapidly after annealing a sample at 450°C, the 30 min anneal raises the relative resistance to 160%. The lowest specific contact resistance of $\rho_c = 0.5\Omega\,\mathrm{cm}^2$ has been measured for 350°C/60 min.

The correlation coefficients r^2 of the $I-V$ curves of Cr/Au contacts on p-GaN are shown in Fig. 9. At 300°C the linearity of the $I-V$ curves improves somewhat, but does not reach the value of 0.99 set as threshold for ohmic behavior (dotted gray line). Annealing at 350 and 400°C raises r^2 above 0.99. Annealing at 450°C decreases r^2 to 0.987 after 30 min, this change is consistent with the counter change in relative contact resistance.

3.4. *Cobalt/gold*

The $I-V$ characteristics of p-GaN/Co/Au contacts have been investigated by cumulative tempering at 350, 450, 600 and 700°C with a total annealing time of 40 min. Fig. 10 shows the change of relative resistance R_{rel}.

After the first anneal at 350°C for 5 min, the relative resistance R_{rel} decreases to 60% and then stays almost constant. The first anneal at 450°C raises R_{rel} to 75%, the next anneal lowers the value back to 60%. A similar though smaller increase of R_{rel} was also observed after the first anneal at 600°C. That behavior is not due to breaks in the sequence of the experiments, this has been checked by measuring R_{rel} a second time directly before loading the sample into the furnace. The mean error of the relative resistance has been calculated to be ±3.5%.

Annealing the samples at 700°C raises the resistance from 60 to 160 %. This drastic increase between 600 and 700°C is due to a 250% increase in sheet resistance from 125 to 310 kΩ, the specific contact resistance raises only 50% from 0.33 to $0.52\,\Omega\,\mathrm{cm}^2$ after the anneal. This behavior was observed only for the cobalt contacts. In all other contact systems the change in R or R_{rel} correlates to that of the specific contact resistance ρ_c, where it could be reasonably measured.

Fig. 11 shows the correlation coefficients of the $I-V$ curves. At 350°C the linearity of the $I-V$ curves improves, r^2 increases. Afterwards it stays at a constant value of about 0.997. The peak of R_{rel} after the first anneal at 450°C is also observed in the mirror-like curve of r^2, subsequent annealing raises r^2 back to about 0.997. The last anneal at 700°C improves the ohmic behavior even though the resistance increases. The lowest specific contact resistance has been measured for 450°C/5 min (cumulated annealing time $t = 20$ min), ρ_c is $0.2\,\Omega\,\mathrm{cm}^2$.

3.5. *Platinum*

Only a few experiments have been done with Pt as contact material on p-GaN. None of the contacts prepared with platinum as contact metal became ohmic, the best value for r^2 as a measure of the linearity of the

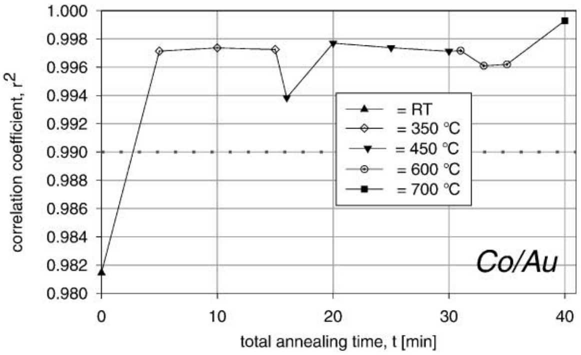

Fig. 11. Correlation coefficient versus cumulated annealing time for p-GaN/Co/Au contacts.

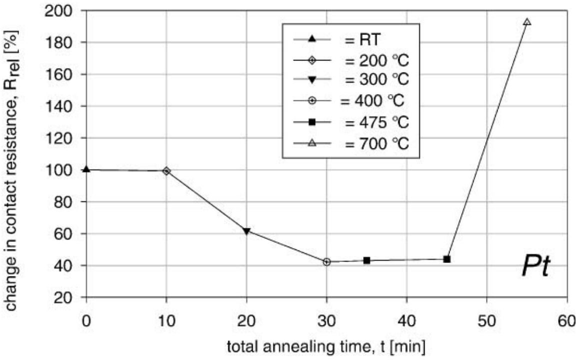

Fig. 12. Relative change of resistance versus cumulated annealing time for p-GaN/Pt contacts.

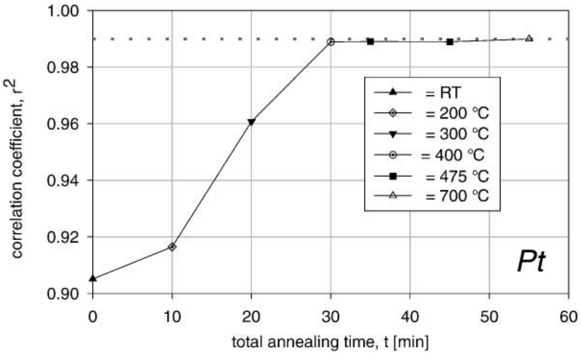

Fig. 13. Correlation coefficient versus cumulated annealing time for p-GaN/Pt contacts.

$I-V$ curves has been 0.989. Fig. 12 shows the relative change of resistance R_{rel} for the best sample, the correlation coefficient is shown in Fig. 13. It should be noted, that the absolute values of the resistance are much higher compared to the other contact metals in this study.

The 10 min anneal at 200°C does not change the resistance of the platinum contact, whereas the value of r^2 increases. Subsequent annealing at 300 and 400°C raises r^2 to almost 0.99, the resistance drops to about 40%. The two following annealing steps change neither R_{rel} nor r^2, the last anneal at 700°C increases the resistance to almost 200%, whereas the linearity of the $I-V$ curves remains constant.

The lowest specific contact resistance of $\rho_c = 1.5\ \Omega\,\mathrm{cm}^2$ has been measured for 475°C/5 min (cumulated annealing time $t = 35$ min). Note that this value is measured on a non-ohmic contact ($r^2 = 0.989$) and is provided for comparison purposes only.

3.6. Gold

Gold has been used as contact metal (Figs. 14 and 15). As observed for platinum, none of the samples become ohmic in the entire annealing cycle. After the first anneal the resistance decreases to about 60%, further annealing at 450 and 600°C does not change this value, considering that the mean error is about 5%. The linearity of the $I-V$ curves improves after the first annealing step as expected by the drop of resistance. Subsequent annealing increases the correlation coefficient of the $I-V$

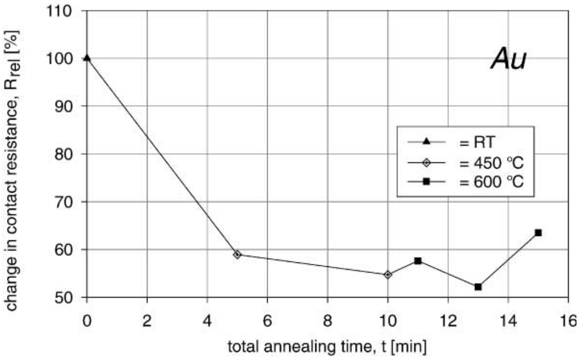

Fig. 14. Relative change of resistance versus cumulated annealing time for p-GaN/Au contacts.

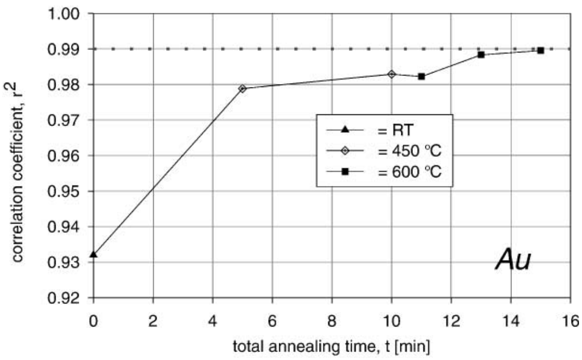

Fig. 15. Correlation coefficient versus cumulated annealing time for p-GaN/Au contacts.

curves from 0.979 to 0.989 after 5 min at 600°C (15 min cumulated annealing time). The lowest specific contact resistance of $\rho_c = 1.0\,\Omega\,\mathrm{cm}^2$ has been measured after 15 min at 450°C for an additional sample. This number is measured on a non-ohmic contact ($r^2 = 0.988$) and is provided for comparison purposes only.

4. Discussion

Summarizing the change of resistance and $I-V$ curve linearity at moderate temperatures (see Table 2), the trends are the same for all the contact metals used except chromium. The contacts improve after annealing at moderate temperatures as determined by a decrease of resistance and more linear $I-V$ curves. Chromium is also an exception in classifying "moderate" temperatures, which include 500°C for all other contact materials, whereas 450°C is a T_{high} for Cr.

No change of sheet resistance of the GaN epi-layer has been observed at T_{moderate} for all contacts, thus the improvement should not be related to the GaN epi-layer. We therefore assume that the improvement of the contact properties is related to changes at the interface metal/p-GaN. Possible explanations are the dissolution of surface contaminants in the metal, the reduction of the native oxide layer of the p-GaN or simply the formation of a more intimate contact between metal and GaN. Oxide reduction would not explain the initial improvement of noble or near-noble metal contacts like Au, Pt or Pd. On the other hand Cr with its high oxygen affinity shows no improvement at moderate temperatures, this also excludes oxide reduction as a probable explanation. Another aspect is the formation of a new phase at the metal/GaN contact, as detailed below.

On other semiconductors like CdTe or SiC, the changes in resistance and $I-V$ curve linearity are often very clearly determined by the formation of reaction phases at the metal/semiconductor interface [5–7]. Evaluating the phase diagrams of metal–Ga–N [8] and the expected reaction products at 500°C (see Table 3), Pd, Ni and Co form binary gallides and nitrogen gas with GaN. Chromium forms two ternary Cr_xGaN phases, located on the straight diffusion path between Cr and GaN, where Cr_3GaN is observed to form as the first reaction product. Pt will show reactions similar to Pd as the phase diagrams Pt–Ga is very similar to Pd–Ga. The formation of a phase Pt_xGa_y has not been checked experimentally.

Table 2
Trends of resistance R_{rel} and ohmic behavior r^2 for anneals at moderate (< 500°C) and high temperatures (> 500°C)

Metal	R_{rel} for T_{moderate}	r^2 for T_{moderate}	R_{rel} for T_{high}	r^2 for T_{high}
Pd	⇓	⇑	⇑	⇑
Ni	⇓	⇑	⇑	⇓
Co	⇓	⇑	⇑	⇑
Pt	⇓	⇑	⇑	⇒
Au	⇓	⇑	⇑	⇒
Cr	⇒	⇑	⇑	⇓

Gold will react with GaN, forming a small amount of a solid Au–Ga solution and nitrogen gas. This has been deduced by interpreting the binary-phase diagrams Au–Ga, Au–N and Ga–N. Assuming the nonexistence of any ternary phases, two variants of the ternary-phase diagram Au–Ga–N are possible, both are drawn schematically in Fig. 16. Interpreting these phase diagrams, a reaction between Au and GaN will come to a halt if the equilibrium of the Au–Ga phase with the GaN is reached. This is the case either in the solid Au–Ga solution (Fig. 16a) or in the liquid Au–Ga phase (Fig. 16b). No formation of droplets has been observed after tempering Au contacts on p-GaN for 5 min at 600°C, thus the reaction after Fig. 16b is either slow or the liquid phase does not form at all. A maximum Ga content of 10% in the solid Au–Ga solution has been concluded from the binary Au–Ga-phase diagram.

Comparing the reactions at the metal/GaN interface (Table 3) with the the measured specific contact resistance ρ_c (Table 4), some relations can be determined. Lower values of ρ_c are obtained on metals forming a gallide phase (Pd, Ni, Co). The formation of a stoichiometric phase like Cr_3GaN, which does not change the ratio Metal : GaN at the contact/semiconductor interface, results in higher values of ρ_c, furthermore the relative resistance does not change after annealing.

Summarizing the impact on the electrical contact properties by phase formation and surface contaminant reduction, the first and main effect at moderate temperatures appears to be the reduction of surface contaminants beneath the contact metal and formation of a more intimate contact. This is concluded from the decrease in relative resistance after thermal treatment, which is observed for all contact metals except Cr. The formation of a reaction phase at the metal/p-GaN interface appears to reduce the specific contact resistance further, the formation of a metal gallide results in the

Table 3
Primary solid reaction products to form at the interface metal/GaN, results for 500°C, taken from [8]

Metal	Reaction product
Pd	Pd_2Ga
Ni	Ni_3Ga
Cr	Cr_2GaN, Cr_3GaN
Co	CoGa

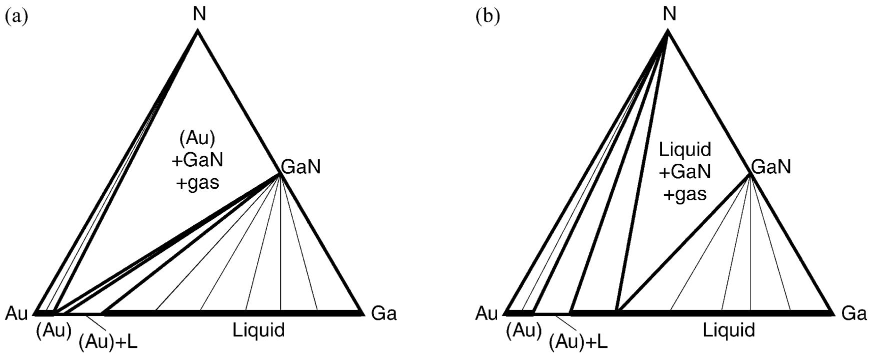

Fig. 16. Schematic phase diagrams Au–Ga–N at 500°C.

Table 4
Specific contact resistance and transfer length for contact materials in this study

Contact metal	Annealing time (min) and temperature (°C)	Specific contact resistance, R_c ($\Omega\,\mathrm{cm}^2$)	Transfer length, L_T (μm)
Ni/Au	15/450	0.1	9
Pd	7.5/450	0.2	14
Co/Au	5/450	0.2	14
Cr/Au	60/350	0.5	23
Au	15/450	1.0[a]	34
Pt	5/475	1.5[a]	47

[a] $I-V$ curve is not linear.

lowest values. This explanation cannot be directly verified, since microscopic measurements (TEM or XTEM) have not been performed.

High-temperature annealing increases the resistance for all contact metals. This is in contrast to the report of [9] who produced a p-GaN/Pt low-resistance ohmic contact ($\rho_c = 1.4 \times 10^{-3}\,\Omega\,\mathrm{cm}^2$) after 10 min at 750°C. He combined the Mg-doping activation anneal with the contact anneal, this might explain the difference to our results (Fig. 12).

A reaction forming a metal gallide is likely for Pd, Ni and Co as discussed above. The removal of Ga atoms by the formation of a metal gallide may produce Ga vacancies, which act as acceptors in p-GaN and thus will improve the contact resistance. High-temperature annealing should foster the gallide formation, which is known to be sluggish in bulk metal/GaN samples at moderate temperatures [8]. However, our electrical results (see Table 4) show that the lowest resistances are observed at moderate temperatures.

The formation of Ga vacancies may be just a theoretical possibility that does not occur in practice, this is supported by a high formation energy of the Ga vacancies in p-GaN as determined by first principle estimation [10]. This means that the gallide forming reaction proceeds with quantitative liberation of nitrogen and diffusional transport to the gas phase above the thin-film contact. In that case no positive effect on p-doping of the GaN right beneath the contact is exerted.

Another explanation for the high-temperature contact degradation is a decomposition of the GaN surface. A decomposition of GaN at 720°C when a nucleation seed for Ga is present is reported in [11]. Without a nucleation seed the GaN layer survives much higher annealing temperatures. In our case this nucleation seed could be the metal contact film on the GaN epi-layer. Gallium can easily migrate by surface diffusion to the metal film and the formation of a metal gallide will even augment the driving force compared to the simple growth of a gallium droplet. The decomposition theory is also supported by TEM experiments on metal films on p-GaN [12], which show a breakup of a p-GaN/Ni interface after an anneal at 600°C/1 min, connected with the formation of a not specified GaN : Ni alloy.

The linearity of the $I-V$ curves as an expression of the ohmic behavior changes differently for the six contact metals after the high-temperature anneal in our experiments. Pd and Co contacts become more linear. Pt and Au contacts do not show a change of the ohmic behavior after the high-temperature anneal, whereas the linearity of the $I-V$ curves of Ni and Cr contacts decreases. No explanation for this behavior can be given.

5. Conclusion

The changes in resistance and $I-V$ curve linearity of Pd, Ni/Au, Cr/Au, Co/Au, Pt and Au contacts on p-GaN after annealing have been investigated. The best values of contact resistivity ($\rho_c = 10^{-1}\,\Omega\,\mathrm{cm}^2$) are observed for Ni/Au, Pd and Co/Au contacts after annealing at moderate temperatures (450°C). Pure Au and Pt contacts show the worst absolute contact resistivity, although their contact resistances improve at moderate temperatures. Chromium contacts already degrade after the moderate 450°C anneal.

The linearity of the experimental $I-V$ curves is quantitatively expressed as the correlation coefficient, r^2, of a linear regression line. The change of linearity correlates clearly to that of the resistance at moderate temperature. Improved linearity is accompanied by a decrease of resistance, the only exceptions are the Cr/Au contacts.

Annealing at higher temperatures (>500°C) increases all the contact resistances, most drastically for Pd and Ni/Au, whereas the change of linearity does not show a clear trend.

A possible explanation for the changes of contact resistance after thermal annealing is given by:

A. Reduction of the native oxide layer on p-GaN.
B. Formation of a reaction phase at the metal/GaN interface.
C. Formation of a more intimate contact between metal and p-GaN epi-layer.
D. Decomposition of the p-GaN epi-layer.

At moderate temperatures (<500°C) factors B and C have the main impact on the decrease of the contact resistance. After annealing the contacts at higher temperatures (700°C), factor C (phase formation) and D (GaN decomposition) influence the terminal contact resistance, which increases while the ohmic behavior of the contacts decreases. The influence of the decomposition on the resulting contact resistance is assumed to be higher than that of the phase formation.

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