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TiAl-based Ohmic Contacts to p-type 4H-SiC

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***Abstract*—This paper describes successfully formed ohmic contacts to p-type 4H-SiC based on titanium-aluminum alloys. Four different metallization structures were examined, varying in aluminum layer thickness (25, 50, 75, 100 nm) and with constant thickness of the titanium layer (50 nm). Structures were annealed within the temperature range of 800°C - 1100°C and then electrically characterized. The best electrical parameters and linear, ohmic character of contacts demonstrated structures with Al layer thickness equal or greater than that of Ti layer and annealed at temperatures of 1000°C or higher.**

***Keywords*—ohmic contact, SiC, silicon carbide, TiAl**

I. Introduction

SILICON carbide is a wide-bandgap material, dedicated to high-power and high-frequency electronics. Due to its extremely high chemical and thermal stability, it is successfully used as a substrate material for power semiconductor devices intended to operate under harsh environmental conditions such as high ambient temperatures and ionizing radiation [1,2]. However, without ohmic contacts that are also able to work in such conditions, full use of potential capabilities of SiC devices is impossible. Exploiting the potential of silicon carbide electro-physical parameters requires from ohmic contacts to SiC-based devices demonstration of low resistivity, stable electrical conductivity, high oxidation resistance and reliability, especially when operating at elevated temperatures. Insufficient electrical conductivity of ohmic contacts due to degradation of metal/SiC interface or relatively high specific contact resistance ρ_c ($>10^{-3}$ Ωcm^2) may result in an unacceptably high voltage drop at the contact, and thereby deterioration or even making impossible operation of silicon carbide devices [3,4].

Currently known and applied methods of fabricating ohmic contacts to n-type SiC are considered satisfactory from the viewpoint of commercial manufacturing of semiconductor devices, while technology of contact forming to p-type SiC still remains a challenge that considerably limits development of high-reliable bipolar device technology. An ideal ohmic contact to p-type semiconductors is made up when work function of the metal is higher than work function of the semiconductor. In practice, such relation may be achieved in two ways: by selecting a metal with appropriately high work function or by increasing the doping level of the semiconductor to 10^{21} cm^{-3}, which allows to lower its potential barrier. However, in the case of p-SiC, increasing the doping to such a high degree is extremely difficult and expensive due to hole mobility lowering and high ionization energy of the dopants (150-200 meV) [5,6]. High value of p-type 4H-SiC work function (~7 eV) [7] considerably limits the assortment of suitable metals, which in combination with silicon carbide, would allow to obtain sufficiently low value of a potential barrier, thus resulting in obtaining ohmic contacts characterized by desired features. Figure 1 depicts the energy band diagram of an ideal metal – p-type semiconductor ohmic contact.

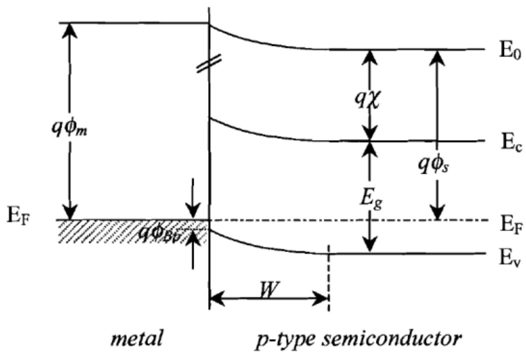

Fig. 1. Energy band diagram of an ideal metal – p-type semiconductor ohmic contact [8]

Nowadays, one of the most commonly used technological solutions to fabricate thermally stable low resistance ohmic contacts to p-type SiC is using of various titanium and aluminum metallization stacks. After high-temperature annealing processes, formation of a material combining the properties of metal and ceramics is observed (Ti_3SiC_2), which is considered to be the phenomenon leading to lowering of the potential barrier height at the metal/SiC junction [4,7,9,10]. Combining titanium and aluminum in the technology of ohmic contacts, formation and their subsequent annealing at sufficiently high temperature, results in obtainng specific resistance at the level of 10^{-4}-10^{-5} Ωcm^2 [2,7,11].

II. Circular Transmission Line Method

One of the best concepts to determine the value of specific contact resistance is the circular Transmission Line Method (c-TLM). The advantage of the c-TLM over classical TLM method is less complex test structures fabrication process, as contacts intended for the TLM require isolation from the substrate, in contrast to c-TLM. There are two types of patterns used for c-TLM: an array of rings, proposed by Marlow and Das

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[12] and concentric rings, designed by Reeves [13]. Difference between them is also related to differences in the calculations required to obtain the specific contact resistance.

c-TLM based on the Marlow's pattern consists of the following steps:

- measurement of the total resistance (R_t);
- linear correction of the measured data with a correction factor;
- simple extrapolation in order to determine contact resistance (R_c) and transfer length (L_t);
- calculation of specific contact resistance (ρ_c) [8].

Linear correction of the measured data for inner radii of contacts rings (L) up to 200 µm and gap spacings (d) ranging from 5 to 50 µm is necessary to compensate the difference between c-TLM and TLM patterns, in order to allow performing adequate calculations. Relation between required correction factor (C) and structure dimensions has been shown in figure 2(a) whereas an example of typical measured and corrected data of circular Transmission Line Method structures along with extrapolation of contact resistance (R_c) and transfer length (L_t) has been shown in figure 2(b).

a)

b)

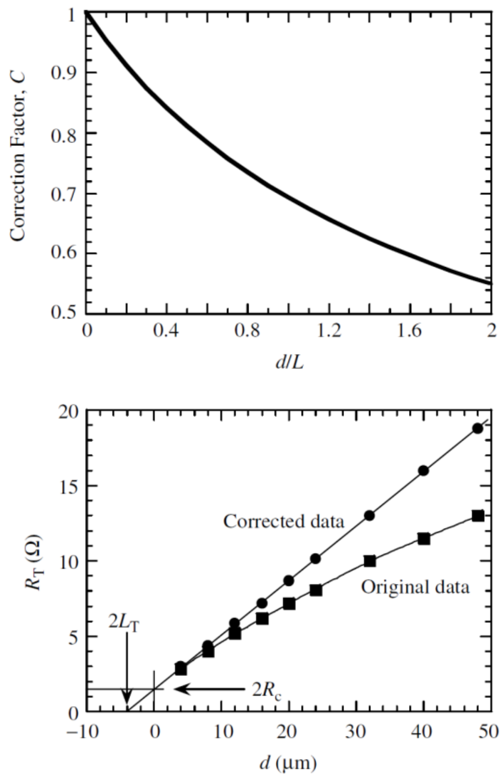

Fig. 2.(a) Correction factor *C* versus *d/L* ratio for the c-TLM test structure, (b) an example of total resistance (R_T) – versus space gaping (*d*) for the c-TLM test structure before and after data correction [8]

III. OHMIC CONTACT FORMATION TO SIC

In order to develop reproducible heterostructures that precisely meet highly defined requirements, phenomena occurring in the interface between forming them materials should be learned and understood. However, the mechanisms of ohmic contacts formation to p-SiC are still not fully known, and therefore this issue still remains a technological challenge requiring further research.

A properly formed ohmic contact to SiC device has to be characterized not only by linear current-voltage dependency and low specific resistivity, but it also should be resistant to negative effects of sustained operation in harsh conditions like potentially elevated temperature, numerous thermal cycles and shocks. Such environment promotes degradation of devices as a result of electromigration processes and intensification of various reactions in the metal/SiC interface, interdiffusion of metal stacks atoms, what might lead to reconstruction of silicides, oxides, carbides or free carbon generation formed in the process of high-temperature annealing [14].

Specific carrier transport mechanisms or their combinations are typically responsible for the ohmic behavior of the metal/semiconductor interface:

- thermionic emission (TE); for lightly-doped semiconductors quite a low metal-semiconductor potential barrier occurs. Consequently, thermally excited electrons can pass over the barrier at the interface;
- field emission (FE); for highly-doped near-contact region of the semiconductor substrate the barrier is sufficiently narrow at or near the contact interface for quantum-mechanical tunneling to take place;
- thermionic-field emission (TFE); for the intermediate doping level of semiconductor substrate. Thermally excited electrons tunnel through the barrier if it is sufficiently narrow, despite of relatively high metal-semiconductor potential barrier [8,14,15].

A widely used metal for ohmic contacts to n-type 4H-SiC is nickel. Due to silicidation at high temperatures (above 900°C), Ni/SiC contacts show low specific contact resistance (less than $1\text{x}10^{-5}\ \Omega\text{cm}^{-2}$) and high reproducibility [16-19]. As nickel reacts mainly with silicon at this temperature level, unreacted carbon diffuses outwards the interface region, resulting in creation of surface defects. In order to ensure temperature stability of contacts, attempts have been made to replace nickel with other materials, e.g. Ti, Pt, W and their alloys [11,15].

While methods of forming ohmic contacts to n-type SiC have been learned to a satisfactory level, the technology of contacts to p-type SiC still remains a challenge which considerably constricts the development of highly reliable bipolar device technology. High value of p-type 4H-SiC work function (~7 eV) makes finding a conventional metal that could lead to low potential barrier formation quite a difficult. The greatest attention is paid to the use of various multilayer combinations of Ti/Al stacks in manufacturing thermally stable ohmic contacts to p-SiC with values of ρ_c within the range of $10^{-4} – 10^{-5}\ \Omega\text{cm}^2$ [2,7,11].

IV. EXPERIMENT DESCRIPTION

The experiment was carried out using commercially available n-type 4H-SiC substrates with a p-type epitaxial layer with a dopant concentration of $N_a = 2\times10^{19}\ \text{cm}^{-3}$ (Cree Inc.). First, a 300 nm thick layer of silicon dioxide was obtained on the substrates surfaces in plasma-assisted chemical vapor deposition process (PECVD), which served as a mask in subsequent technological processes. Then, using photolithography and plasma etching of the SiO_2 layer processes, patterns of c-TLM structures of Marlow's design were produced (Fig. 3). Inner circle with a diameter of 50 µm was constant for all structures whereas the spacing gaps were equal to 5, 10, 15, 20, 25, 30, 35, 40 and 45 µm.

Contacts metallization was made of titanium layer of constant thickness (50 nm) and aluminum layers of different thickness (25, 50, 75 or 100 nm). The metallization was deposited on the silicon carbide substrate by magnetron sputtering using the Plasmalab System 400 by Oxford Instruments. Subsequently, in the lift-off process, TiAl layers were removed from the 4H-SiC surface around the ohmic contacts. Afterwards, the structures were annealed in RTP reactor at 800°C, 900°C, 1000°C and 1100°C for 5 minutes in the argon (95%) / hydrogen (5%) atmosphere.

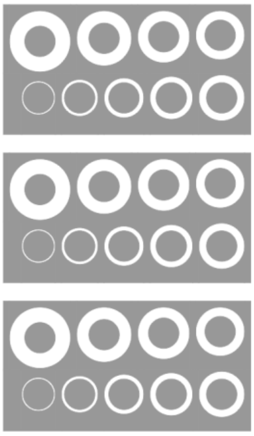

Fig. 3. The pattern of fabricated ohmic contacts

V. OHMIC CONTACTS CHARACTERIZATION

Characterization of fabricated ohmic contacts was performed using two-point method and consisted of two stages. First, in order to estimate linearity and inclination of I-V characteristics as well as to determine the influence of the parameters of individual processes performed during fabrication on the final parameters of the ohmic contacts, measurements were conducted on two pads of the same dimensions, located 25 µm apart.

Reproducible, linear characteristics were obtained for structures annealed at 1000°C and 1100°C with aluminum layer thickness the same as, or greater than the thickness of the titanium layer (Fig. 4). In the case of lower annealing temperatures (800°C and 900°C), drastic deterioration of the structures conductivity was observed, which is the typical phenomenon, reported in numerous scientific publications concerning Ti/Al ohmic contacts [2,4,14,15].

The surface morphology analysis of four types of Ti/Al metallization after all annealing steps was performed using the Olympus Lext confocal microscope (Fig. 5). Significant development of the surface roughness was observed in the case of contacts annealed at 1000°C and 1100°C. Changes in the structure of the metallization surface are greater the thicker aluminum layer is and the higher the annealing temperature is. Moreover, between the metallization of contacts with a thicker Al layer, a reaction with the field oxide surrounding the contact was observed. The above-mentioned effects may have vast negative impact on the stability and reproducibility of the subsequent assembly processes and the implementation of electrical connections of devices.

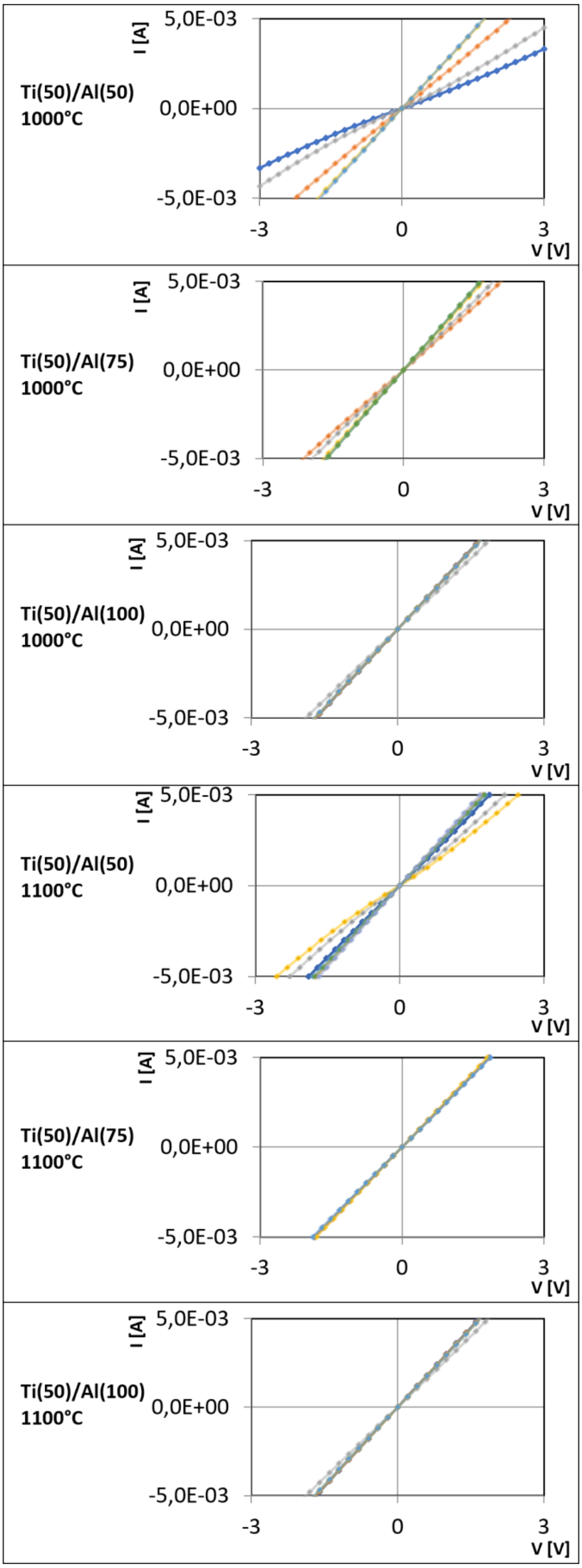

Fig. 4. Current-voltage characteristics of selected Ti/Al ohmic contacts to p-SiC annealed in Ar:H2 ambient

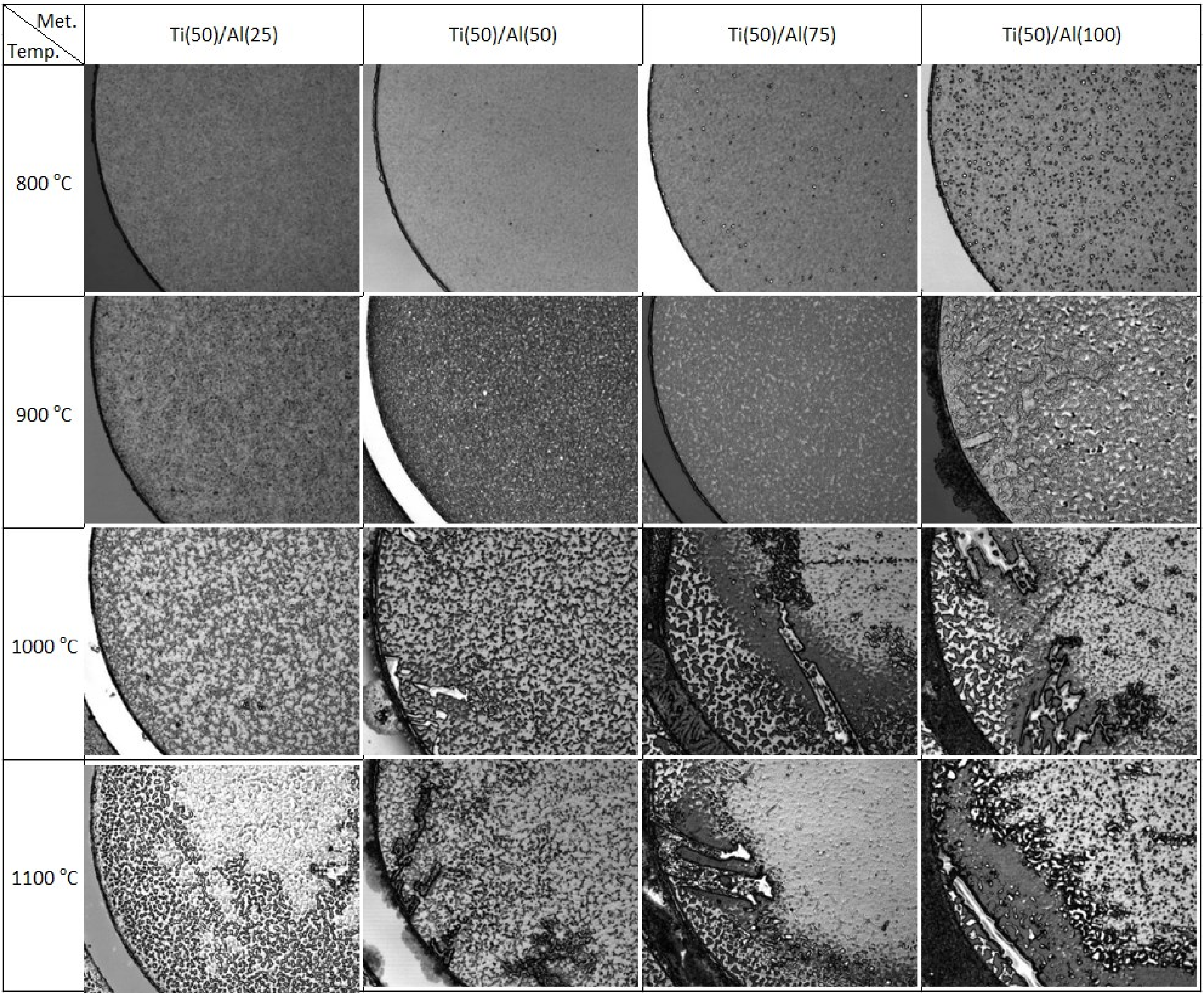

Fig. 5. Confocal microscope images of Ti/Al contacts to p-SiC annealed in Ar:H2 ambient

The second part of electrical measurements was conducted for selected samples exhibiting fully linear I-V characteristics with a high slope. The electrical characterization of all produced c-TLM structures with different geometric parameters was carried out according to the procedure presented in section II of this paper.

Based on the measurement results shown as $R_t(d)$ dependency (Fig. 6,7), and an appropriate correction factor C, contact resistance R_c, and transfer length L_t were determined. Values of surface resistance of the substrate R_{sh} (common for all structures) and specific resistances ρ_c were calculated using formulas (1), (2), where L states for inner circle radii while d states for the gap spacing. Characterization results have been presented in Table 1. The best structure demonstrated specific contact resistance of $\rho_c = 5.3 \times 10^{-4}\ \Omega cm^2$.

$$R_t = \frac{R_{sh}}{2\pi L}(d + 2L_t)C \qquad (1)$$

$$\rho_c = R_{sh} \times L_t^2 \qquad (2)$$

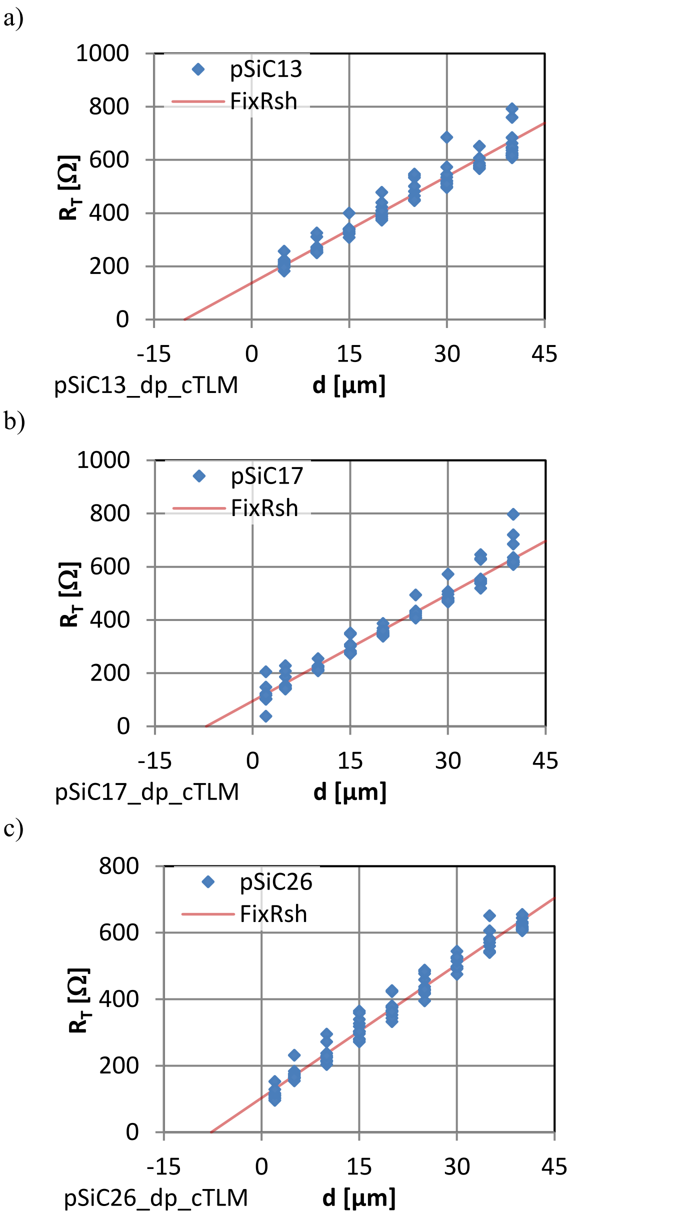

Fig. 6. Total resistance of ohmic contacts to p-SiC formed at 1000°C in Ar:H_2 before and after data correction for the following metallizations: a) Ti(50 nm)/Al(50 nm), b) Ti(50 nm)/Al(75 nm), c) Ti(50 nm)/Al(100 nm)

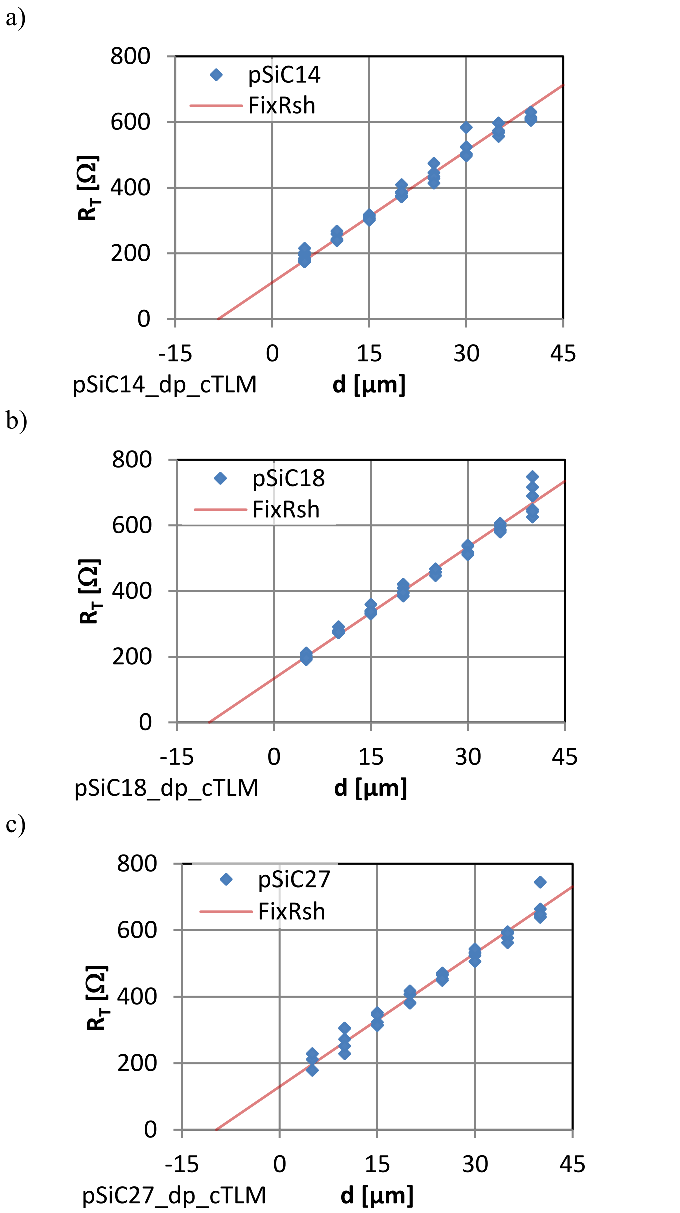

Fig. 7. Total resistance of ohmic contacts to p-SiC formed at 1100°C in Ar:H_2 before and after data correction for the following metallizations: a) Ti(50 nm)/Al(50 nm), b) Ti(50 nm)/Al(75 nm), c) Ti(50 nm)/Al(100 nm)

TABLE I
EXTRACTED AND CALCULATED PARAMETERS OF FABRICATED OHMIC CONTACTS TO P-SIC

Metallization Stack	Temperature (°C)	Sheet Resistance R_{sh} (Ω/sq)	Contact Resistance R_c (Ω)	Transfer Length L_t (µm)	Specific Contact Resistance ρ_c (Ωcm^2)
Ti (50nm)/ Al (50nm)	1000	4200	69	5.1	1.1×10^{-3}
Ti (50nm)/ Al (50nm)	1100	4200	56	4.2	7.3×10^{-4}
Ti (50nm)/ Al (75nm)	1000	4200	48	3.6	5.3×10^{-4}
Ti (50nm)/ Al (75nm)	1100	4200	67	5.0	1.0×10^{-3}
Ti (50nm)/ Al (100nm)	1000	4200	52	3.9	6.3×10^{-4}
Ti (50nm)/ Al (100nm)	1100	4200	65	4.9	9.9×10^{-4}

Conclusion

As a part of the presented research, Ti/Al ohmic contacts to 4H-SiC (p type) with low specific resistivity were produced by high-temperature annealing. The influence of the process temperature in the range of 800°C - 1100°C on electrical properties of four groups of structures with Ti/Al metallization, with 50 nm thick titanium layer and varying in thickness (25 nm, 50 nm, 75 nm or 100 nm) aluminum layers, was investigated.

Ohmic structures and desired I-V characteristics resulted from 5 min annealing processes at temperatures of 1000°C and 1100°C in argon and hydrogen atmosphere of contacts with the thickness of the aluminum layer greater than or equal to the thickness of the titanium layer. Ohmic contacts with the best properties ($\rho_c = 5.3\times10^{-4}$ Ωcm2) were obtained by annealing structures with Ti (50 nm)/Al (75 nm) metallization at the temperature of 1000°C.

References

[1] T. Ohshima, S. Onoda, N. Iwamoto, T. Makino, M. Arai, and Y. Tanak, "Radiation Response of Silicon Carbide Diodes and Transistors," in *Physics and Technology of Silicon Carbide Devices*, 2012. DOI: 10.5772/51371.

[2] Y. Zhang, T. Guo, X. Tang, J. Yang, Y. He, and Y. Zhang, "Thermal stability study of n-type and p-type ohmic contacts simultaneously formed on 4H-SiC," *J. Alloys Compd.*, vol. 731, pp. 1267–1274, 2018. DOI: 10.1016/j.jallcom.2017.10.086.

[3] Y. Huang, J. Buettner, B. Lechner, and G. Wachutka, "The impact of non-ideal ohmic contacts on the performance of high-voltage SIC MPS diodes," *Mater. Sci. Forum*, vol. 963 MSF, pp. 553–557, 2019. DOI: 10.4028/www.scientific.net/MSF.963.553.

[4] F. Roccaforte *et al.*, "Ti/Al-based contacts to p-type SiC and GaN for power device applications," *Phys. Status Solidi Appl. Mater. Sci.*, vol. 214, no. 4, 2017. DOI: 10.1002/pssa.201600357.

[5] M. Rambach, A. J. Bauer, and H. Ryssel, "Electrical and topographical characterization of aluminum implanted layers in 4H silicon carbide," *Phys. Status Solidi Basic Res.*, vol. 245, no. 7, pp. 1315–1326, 2008. DOI: 10.1002/pssb.200743510.

[6] F. Roccaforte, F. Giannazzo, and V. Raineri, "Nanoscale transport properties at silicon carbide interfaces," *J. Phys. D. Appl. Phys.*, vol. 43, no. 22, 2010. DOI: 10.1088/0022-3727/43/22/223001.

[7] T. Abi-Tannous *et al.*, "A Study on the Temperature of Ohmic Contact to p-Type SiC Based on Ti3SiC2 Phase," *IEEE Trans. Electron Devices*, vol. 63, no. 6, pp. 2462–2468, 2016. DOI: 10.1109/TED.2016.2556725.

[8] D. K. Schroder, *Semiconductor Material and Device Characterization*, 3rd ed. New Jersey: John Wiley & Sons, Inc., Hoboken, 2006.

[9] K. Buchholt *et al.*, "Ohmic contact properties of magnetron sputtered Ti3SiC2 on n- and p-type 4H-silicon carbide," *Appl. Phys. Lett.*, vol. 98, no. 4, pp. 2–5, 2011. DOI: 10.1063/1.3549198.

[10] T. Abi-Tannous *et al.*, "Thermally stable ohmic contact to p-type 4H-SiC based on Ti3SiC2 phase," *Mater. Sci. Forum*, vol. 858, pp. 553–556, 2016. DOI: 10.4028/www.scientific.net/MSF.858.553.

[11] F. Roccaforte *et al.*, "Metal/semiconductor contacts to silicon carbide: Physics and technology," *Mater. Sci. Forum*, vol. 924 MSF, pp. 339–344, 2018. DOI: 10.4028/www.scientific.net/MSF.924.339.

[12] G. S. Marlow and M. B. Das, "The effects of contact size and non-zero metal resistance on the determination of specific contact resistance," *Solid State Electron.*, vol. 25, no. 2, pp. 91–94, 1982. DOI: 10.1016/0038-1101(82)90036-3.

[13] G. K. Reeves, "Specific contact resistance using a circular transmission line model," *Solid State Electron.*, vol. 23, no. 5, pp. 487–490, 1980. DOI: 10.1016/0038-1101(80)90086-6.

[14] Z. Wang, W. Liu, and C. Wang, "Recent Progress in Ohmic Contacts to Silicon Carbide for High-Temperature Applications," *J. Electron. Mater.*, vol. 45, no. 1, pp. 267–284, 2016. DOI: 10.1007/s11664-015-4107-8.

[15] M. Vivona, G. Greco, C. Bongiorno, R. Lo Nigro, S. Scalese, and F. Roccaforte, "Electrical and structural properties of surfaces and interfaces in Ti/Al/Ni Ohmic contacts to p-type implanted 4H-SiC," *Appl. Surf. Sci.*, vol. 420, pp. 331–335, 2017. DOI: 10.1016/j.apsusc.2017.05.065.

[16] S. Rao, G. Pangallo, and F. G. Della Corte, "Highly Linear Temperature Sensor Based on 4H-Silicon Carbide p-i-n Diodes," *IEEE Electron Device Lett.*, vol. 36, no. 11, pp. 1205–1208, 2015. DOI: 10.1109/LED.2015.2481721.

[17] L. Lanni, B. G. Malm, M. Ostling, and C. M. Zetterling, "500°C bipolar integrated OR/NOR Gate in 4H-SiC," *IEEE Electron Device Lett.*, vol. 34, no. 9, pp. 1091–1093, 2013. DOI: 10.1109/LED.2013.2272649.

[18] W. Sung and B. J. Baliga, "Monolithically Integrated 4H-SiC MOSFET and JBS Diode (JBSFET) Using a Single Ohmic/Schottky Process Scheme," *IEEE Electron Device Lett.*, vol. 37, no. 12, pp. 1605–1608, 2016. DOI: 10.1109/LED.2016.2618720.

[19] C. Han *et al.*, "An Improved ICP Etching for Mesa-Terminated 4H-SiC p-i-n Diodes," *IEEE Trans. Electron Devices*, vol. 62, no. 4, pp. 1223–1229, 2015. DOI: 10.1109/TED.2015.2403615.