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OHMIC CONTACTS TO InN-BASED MATERIALS

The key aspects of ohmic contact formation to InN-based materials were investigated. Detailed analysis of studies conducted over the past three decades, allows determining the basic principles of such contacts. The contact structure properties and optimal conditions for them are presented. Different types of metallization are considered, the advantages and disadvantages of each are determined, including the basic requirements that such contact must meet. There is emphasis on the using multilayer metallization with the barrier layers. In the case of the InAlN/GaN systems, the general approaches of forming ohmic contacts were considered.

Keywords: ohmic contact, Indium Nitride, contact resistivity, rapid thermal annealing.

Nowadays, indium nitride (InN) as III-nitride compound (A^3N) attracts rapid interest among researchers from around the world. Mostly this is due to the breakthrough in InN growth. The most quality material is grown by metalorganic vapour phase epitaxy (**MOVPE**) and plasma-activated molecular beam epitaxy (**PAMBE**). Considering the fact that the synthesis of epitaxial InN films originated in the second half of the 70s, however only in 2002 the group of researchers headed by Davydov V. Yu et al. [1] found that this is a semiconductor with a narrow band gap of 0.7 eV in contrast to 1.9 eV, as previously thought. It follows that only $In_xGa_{1-x}N$ can span the entire visible wavelength range, and $In_xAl_{1-x}N$ overlap the wavelength range from infrared to ultraviolet (**Fig. 1**).

The attention focused on InN has increased significantly at the beginning of the XXI century.

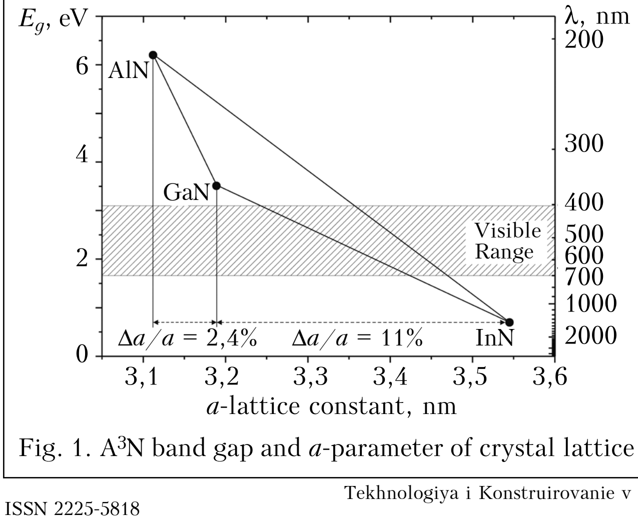

Fig. 1. A^3N band gap and *a*-parameter of crystal lattice

The various studies conducted in several papers [1—8] prevented the re-evaluation of the most important electrical InN parameters (**Table 1**). These data indicate the lowest effective mass for electrons among A^3N semiconductors [2], high saturation velocity [6] and high mobility [7]. All the superior electric properties of this material make InN a highly potential semiconductor for the fabrication of high-speed electronic devices. The terahertz (THz) emission with the maximum at the 3—5 THz is observed under electrical pumping from InN epilayers [9, 10], it makes this material promising for portable THz emitters.

Most A^3N films are grown on substrates such as sapphire (Al_2O_3), silicon (Si) or silicon carbide (SiC), because single crystals of III-nitride cannot be grown easily. The absence of homogeneous (crystallographically coordinated) substrates for (In,Ga,Al)N growth is one of the distinctive feature of A^3N growth. The epitaxial InN growth on GaN buffer layer is the best case, however significant mismatch of the lattice parameters *a* and thermal expansion coefficients α of the InN/GaN heterostructure must be considered. There are $\Delta a/a$ = +11% and $\Delta\alpha_a/\alpha_a$ = −38%, respectively (Fig. 1). Such heteroepitaxial growth usually results in high level of structural defect density, due to the relaxation of local mechanical stresses on the InN/substrate interface.

X-ray diffraction (**XRD**), transmission electron microscopy (**TEM**), atomic force microscopy (**AFM**) are the most commonly encountered methods of investigating structural defects density in A^3N films. According to the recent structural studies [11—14] of epitaxial indium nitride films grown by MOVPE or PAMBE onto different

Table 1

Comparison of common semiconductor parameters [1—8, 15, 16]

Parameters at 300 K	InN (wurtzite)	AlN (wurtzite)	GaN (wurtzite)	GaN (zinc bland)	4H-SiC (wurtzite)	Si (diamond)
Band gap E_g, eV	0.70	6.20	3.51	3.30	3.25	1.12
Effective electron mass, m_e/m_0	0.04	0.40	0.20	0.13	0.42	0.19
Mobility of electrons μ, см^2/(V·s)	2500	1100	1300	1000	800	1350
Saturation velocity v_s, ·10^7 cm/s	5.6	1.9	3.0	3.0	2.0	1.0
Crystal lattice parameters a,c, nm	a = 0.355 c = 0.570	a = 0.275 c = 0.498	a = 0.319 c = 0.519	a = 0.452	a = 0.308 c = 1.510	a = 0.543
Linear thermal expansion coefficient α, ·10^{-6} K^{-1}	α_a= 3.80 α_c= 2.90	α_a= 4.15 α_c= 5.27	α_a= 5.59 α_c= 3,17	—	α_a= 4.30 α_c= 4.70	α_a= 2.60
Melting point, T, °C	1100	3000	2500	2500	2830	1420
Dielectric constant, ε	15.3	9.1	8.9—9.5	9.7	9.7	11.8

substrates such as Si, SiC and Al_2O_3, provide that threading dislocations are prevailing type among all known defects in InN layers. This type of defects can grow deeper and extend the semiconductor device active areas. Meanwhile, threading dislocations significantly affect both the characteristics of InN-based devices and the parameters of contacts to them. The density of dislocations usually is characterized by the wide range of high value from 10^9 cm^{-2} to 10^{11} cm^{-2}, depending on the growth parameters and film thickness.

The next important problem is creating ohmic contacts to the indium nitride films with high density of structural defects. Such contacts must satisfy a large set of requirements. There are technological requirements for their production process, requirements for reliability of such contacts and requirements to achieve an excellent electrical parameters of future contacts.

It should be pointed out that during the past years, a set of previous researches [17—52] uncovered important useful data about the ohmic contacts to In-based materials. Unfortunately, none of these researches could offer the complete picture. Therefore, in this study, our objective is to investigate them in more detail, and to explore, in the light of all these, principles of metal/InN ohmic contact formation. We plan to consider different types of metallization and to determine the advantages and disadvantages of each. At the end of present paper, the common approaches for ohmic contacts to InAlN/GaN heterostructures will be considered.

Conditions of ohmic contact formation

An ohmic contact is a metal/semiconductor contact exhibit linear current-voltage (I-V) characteristics in a range of operating currents. The contact resistivity (ρ_c), temperature dependence of contact resistivity ($\rho_c(T)$), maximum working temperature are the main characteristics of ohmic contact.

Depending on the purpose of ohmic contacts, in other words on the complexity and type of load during operation, these contacts consist of a single layer (single-layer) or several layers (multilayer) of metallization, each of them has its own functionality:

1. Contact layer — metallization layer that is directly responsible for the formation of a potential metal-semiconductor barrier, because it formed in the immediate vicinity of semiconductor. Moreover, it should limit the diffusion of the upper metals onto the semiconductor surface;
2. Doping layer — thin layer between a semiconductor and a contact layer used for additional doping of the semiconductor near-surface layer, which is commonly used to implement the tunneling mechanism of current flow in ohmic contacts and reduce the contact resistivity;
3. Over layer — layer that is used for compensating of mechanical stresses caused by the significant mismatch of the lattice parameters and thermal expansion coefficients;
4. Barrier layer — refractory metallic layer, limiting inter-diffusion between contact and outer metallization layers;
5. Adhesion layer — metallic layer formed between the outer layers and contact layer, it is used to improve the wetting of the lower layer of material that is applied after the adhesion layer. As a result increases mechanical strength of general ohmic contact metallization;
6. Cap layer — metallic layer is designed to connect contact with external terminals to switch on the device in the electrical circuit. On the other hand, it acts as protective layer to minimize or prevent the oxidation of the underlying metals.

Ohmic contact can be formed in the following cases:

1. Absence of the metal—semiconductor potential barrier. In this case an electron work function of a metal (φ_m) must be less than an electron affinity of a *n*-type semiconductor (χ). In case of p-type semiconductor reversed condition ($\varphi_m > \chi$) must be satisfied.

Implementation of the first case by selecting contact metal with a required work function for indium nitride is almost impossible due to the existence of high-density surface charges [17]. It can significantly exceed the concentration of majority carriers. As a result, the surface charges significantly affect the energy diagram of the metal—semiconductor heterojunction that is virtually independent of the work function of the contact metal [18]. Managing the concentration of surface states usually carried out using various technological treatments semiconductor films. There are the processes of preparing the semiconductor surface before the metal deposition, process of metal deposition, annealing process of formed contacts. Therefore given processes will significantly affect the ohmic contact resistivity — one of the most important parameters.

2. The presence of the narrow metal—semiconductor potential barrier that allows electrons to tunnel through the barrier. To form ohmic contact in this case the additional doping of contact layer is often used. As a result the space charge region is so thin that quantum-mechanical tunneling of charge carriers is possible. However, InN films are usually characterized by the high electron concentration in the range of 10^{17}—10^{20} cm^{-3} due to the growth specifics [5]. This fact contributes to the formation of low-resistance ohmic contact to the semiconductor without additional doping of near-surface semiconductor layers. Moreover, the significant concentration of surface states facilitates a solution to the problem of formation of a narrow potential barrier.

3. The case of the sufficiently low metal—semiconductor potential barrier. It is necessary for possibility of carriers to flow over the barrier. The low-barrier contacts usually are formed due to the realization of surface pretreatment and subsequent correct selection of metallization layers for deposition onto the semiconductor surface.

4. The presence of semiconductor layer shorted by metal shunts that can be caused by the deposition of metal atoms on dislocations or other structural defects [19]. This case is high probably for indium nitride films with high density of structural defects. It was confirmed that the increasing temperature dependences of the contact resistivity $\rho_c(T)$ obtained for ohmic contacts to InN can be explained by current flow through dislocations associated with metal shunts [20].

To date, the temperature dependence of ohmic metal/InN contacts resistivity (ρ_c) is not fully investigated. For fixed values of the barrier height and carrier concentration, the temperature dependence of contacts resistivity determines the carrier transport mechanism through the metal/semiconductor interface. The field emission is one of the frequently occurred transport mechanisms due to heavily doped semiconductor films [21—24].

The anomalous increase in the temperature dependence of contact resistivity, $\rho_c(T)$, was obtained by the authors of [25, 26], who attempted to explain the increase by the metallic conductivity in degenerate InN [26]. However, no direct measurements of $\rho_c(T)$ were performed in this work. In addition, the affect of a high density of structural defects was not taken into account.

The necessity of structural studies for fully understanding the carrier transport mechanisms of ohmic contacts to InN-based films was demonstrated in [27]. Investigation of Ti/Al/Au ohmic contacts to InAlN/AlN/GaN found a significant influence the TiN contact inclusions (spike) in GaN layers on a current flow.

Prior to metal deposition the surface treatment of InN films usually can be carried out in several steps each of which performs a separate problem [22, 28—30]. In many cases the first step is the removing native oxides by dipping the samples in H_2O:NH_4OH(20:1) for 1 min. Subsequently, the second step is the etching in HCl:H_2O (1:3) solution to remove the possible In on the top surface. For the third step HF:H_20 (1:50) are used. Finally, InN films are rinsed with deionizer water.

For the correct selection of contact metal a host of factors must be considered. There are the distinctive features of semiconductor that define the bending of energy bands in the surface region of the semiconductor; the adhesion of metal to a semiconductor; the lattice mismatch effect in metal/semiconductor interface (the parameters of commonly used metals for creating ohmic contacts to InN, are shown in the **Table 2**), etc.

However, all of the above requirements are insufficient for creating the low resistance ohmic contact. One possibility is that the rectifying contact can be formed after metal deposition onto unwarmed substrate. In this case rapid thermal annealing (**RTA**) is used for manipulating of the height and width of potential barrier due to the forming n^+ and p^+ layers. However, the relatively low temperature of InN dissociation (630°C in vacuum and 500°C in an atmosphere of N^2 [3]) must be consider during the thermal treatments. Investigation of surface morphology and elemental composition of single crystal indium nitride surface [31, 32] confirm low thermal stability compared to the other compounds of III-nitride group. The degradation of structure was observed during thermal treatments in a nitrogen atmosphere at temperatures above 550°C due to InN dissociation and subsequent N loss from the nitride surface are found to occur.

Thus, the formation of ohmic contacts to InN is a sequence of complex processes that is

Table 2

Parameters of metals and alloys used for forming ohmic contacts to InN*

Metal	W, eV	Melting point,°C	a_0, nm	α, $\cdot 10^{-6}/K^{-1}$	ρ, Ω·μm
Ag	4.30	960	0.409	18.90	0.015
Al	4.25	660	0.405	22.30	0.026
Au	4.25	1063	0.408	14.00	0.023
Hf	3.80	2230	0.319	6.00	
Mo	4.30	2620	0.315	5.27	0.050
Nb	3.95–4.87	2468	0.330		0.152
Ni	4.50	1453	0.352	13.20	0.068
Pb	4.20	327	0.495	28.30	0.190
Pd	4.80	1550	0.389	11.75	0.108
Pt	5.32	1770	0.392	9.50	0.098
Ta	4.12	2996	0.331	6.60	0.124
Ti	3.95	1608	0.295	8.10	0.470
Zr	3.90	1855	0.323	7.36 – 4.99	0.410
V	4.30	1887	0.302	10.60	0.248
W	4.54	3400	0.316	4.40	0.055
WSi_2	4.05	2160			
TiB_2	3.80	2790	0.323	5.50	
TiN	2.92–4.09	2950		4.70	

* W — work function of the metal, ρ — resistivity.

caused by the necessity to take into account the distinctive features of a semiconductor and wide set of requirements that the contact must meet. The main requirements can be classified as follows:

1. Technological requirements:

— avoidance of device characteristics changing during the formation of contacts;

— possibility of selective etching of metals in the process of photolithography;

— ability to use of technological impacts for controlled change of electrophysical contact characteristics;

— manufacturing process of that contacts must be as simple as possible and consistent with the production of semiconductor.

2. Electric requirements:

— sufficiently low contact resistivity for avoidance of a significant voltage drop at the contact and its additional heating;

— symmetric and linear I-V characteristics in a range of operating currents;

— avoidance of minority-carrier injection.

3. Requirements for reliability:

— stability of contact properties to prolonged electrical and thermal loads during operation;

— reasonable adhesion of contact metal to InN;

— use of materials with similar thermal expansion coefficient and crystal lattice parameters;

— preservation of the contact structural homogeneity during long-term operation of the device for avoiding substantial change in contact parameters.

Minimal ohmic contact resistivity limits to *n*-InN

The contact resistivity is an important parameter characterizing the metal/semiconductor interfaces. It consists of near-contact area resistivity of semiconductor and series connecting resistivity caused by current flow over the potential barrier. Minimal ohmic contact resistivity limits ($\rho_{c\ \min}$) to widely used n-type semiconductors was derived in [33], giving the lowest possible ohmic contact resistivity for nondegenerate and degenerate metal—semiconductor. It was assumed that the potential barrier is absent during the semiconductor—metal current flow and probability of tunneling in the same direction tends to 1.

In accordance with this assumption the final minimal contact resistivity $\rho_{c\ \min}$ is:

$$\rho_{c\,\min} = \frac{k}{qAm^{*}T}\exp\left(\frac{qV}{kT}\right) = \frac{k}{qAm^{*}T}\cdot\frac{N_c}{N_d}\ , \quad (1)$$

where k — Boltzmann's constant;
q — elementary electric charge;
A — Richardson constant ($A = 120$ A·cm^{-2}·K^{-2});
$m^* = m_e/m_0$, m_e and m_0 — effective mass and free electron mass respectively;
T – temperature;
$N_c = 2(2\pi kTm^*/h^2)^{3/2}$ — effective density of states in the conduction band;
N_d — electrically active bulk doping concentration.

In compliance with [33], we estimated the minimal ohmic contact resistivity limits in case of n-InN:

$$\rho_{c\,\min} = 1.15 \cdot 10^9 [\mathrm{Ohm} \cdot \mathrm{cm}^{-1}\,\mathrm{K}^{-1/2}] \frac{\sqrt{T}[\mathrm{K}^{1/2}]}{N_d[\mathrm{cm}^{-3}]}. \quad (2)$$

For instance, the obtained minimal contact resistivity is 3.91·10^{-8} Ohm·cm^2 for $N_d = 5 \cdot 10^{17}$ cm^{-3} at T = 300 K.

Contacts based on a single-layer metallization

The most simple in terms of technology and low-cost variant is the formation of ohmic contacts based on single-layer metal structures. For selection of such metal structures one gives the most important attention to the next parameters. There are conductivity, adhesion to a semiconductor, electron work function and metal melting point.

The wolframium (W) and wolframium silicide (WSi_x) layers are the most common single-layer ohmic contacts to the n-InN. Previously these metal layers take priority during choosing the material for forming single-layer ohmic contacts to the n-InN due to the low resistivity and high melting point (Table 2).

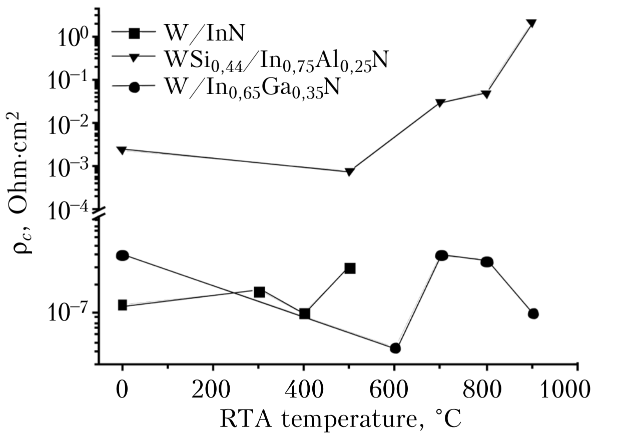

Fig. 2. Contact resistivity for W, WSi_x contacts as a function of annealing temperature [28, 29]

The conducted in [21, 22, 28, 29, 34, 35] studies of W/n-InN and WSi_x/n-InN indicate the high thermal stability of these structures. The physical properties of the obtained contacts to InN, $In_xAl_{1-x}N$ and $In_xGa_{1-x}N$ films degraded after RTA at temperature higher than 400°C, 500°C and 600°C, respectively [28, 29]. It was confirmed by the sharp contact resistivity increasing after appropriate thermal treatments (**Fig. 2**).

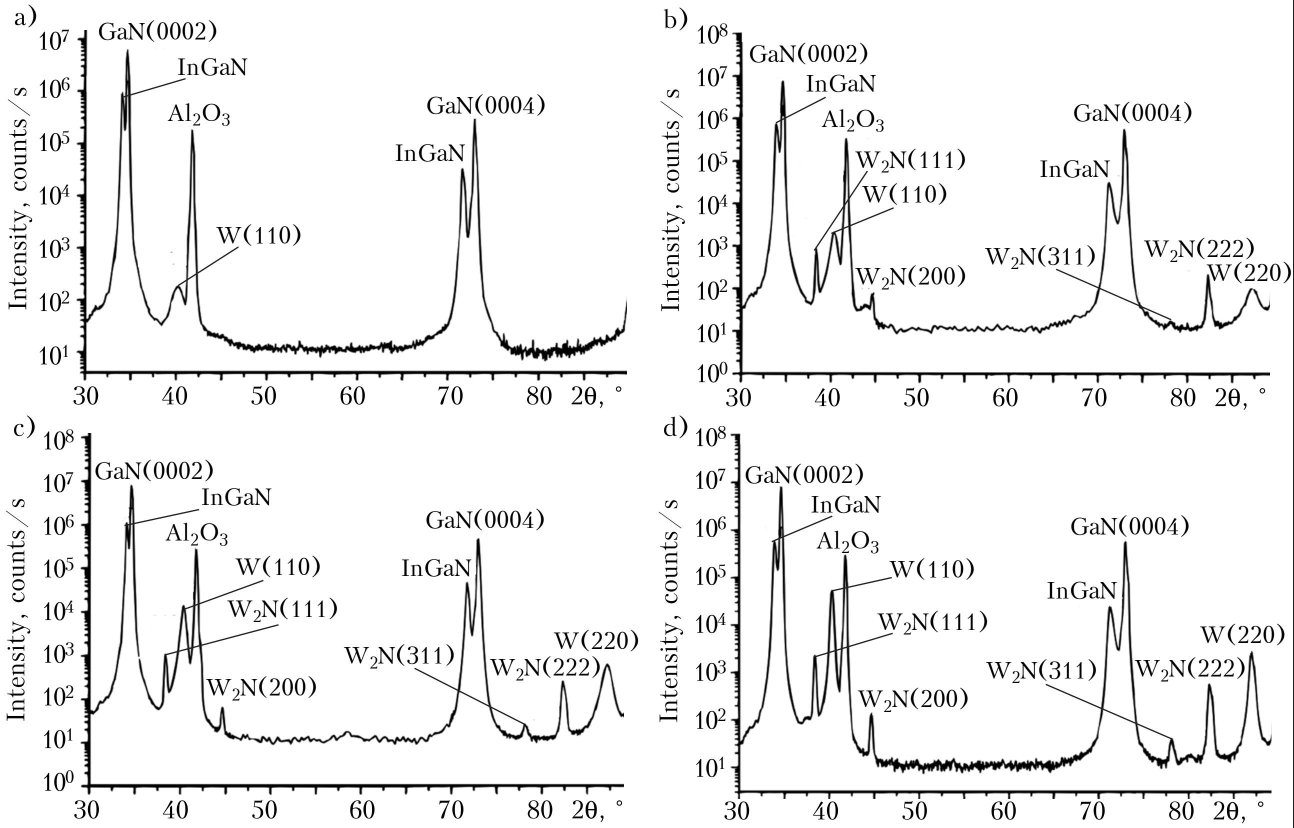

Рис. 3. XRD data for the W/InGaN samples as-deposited (a) and annealed at 500°C (b), 700°C (c), and 950°C (d) [34]

One of the main causes of contact resistance decreasing during RTA for contacts based on single-layer metallization (W, WSi_x) could be forming of the interfacial phase of wolframium nitride (W_2N), its appearance was confirmed by X-ray diffraction studies (**Fig. 3**). W_2N was formed after RTA at 500°C. In addition, the interfacial W_2N phase became better defined with increasing temperature, indicating the occurrence of the more extensive interfacial reactions. This indicates that the nitrogen is outdiffused from a semiconductor, resulting in the accumulation of nitrogen vacancies near the semiconductor surface. These nitrogen vacancies are likely to act as donors. Thus, the increase in the carrier concentrations near the surface layer is responsible for the improved *I-V* characteristics.

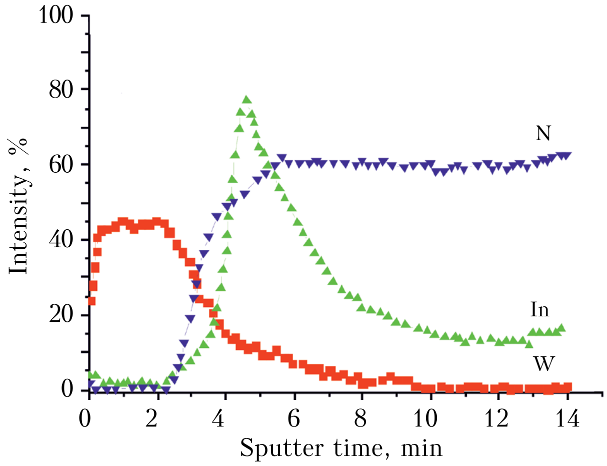

Fig. 4. AES depth profiles of W/InN after RTA at 500°C [21]

A major disadvantage of such contact-layer formation is the considerable thickness of heterogeneous interface formed after RTA, it is confirmed by AES depth profiles (**Fig. 4**) [21]. Therefore, these contacts are not suitable for all modern semiconductor devices that often require the unfloatable ohmic contacts with thin boundary dividing metal and semiconductor. The main work directions on these problems are introduction additional layers of metallization and reduction the temperature of annealing treatment or complete exclusion of RTA.

Bilayer ohmic contacts based on Al, Ni, Ti

Ti-based ohmic contacts to *n*-InN are widely distributed due to high melting point of this metal (1608°C), low resistance and crystal growth parameters related with InN. However, Ti layer has high propensity to oxidation (the formation of high-resistance titanium oxide compounds). Thus, it is used with Al or Au top layers to prevent diffusion of titanium on the surface and its oxidation. Minimal contact resistivity $1.2 \cdot 10^{-7}$ Ohm·cm^2 of such structures was obtained after 500°C RTA for 15 s (**Table 3**) [21]. A further increase of the annealing temperatures (600°C) leads to abrupt increase of the values of ρ_c. A more detailed analysis of Ti/InN interface found the diffusion of Ti into semiconductor and significant diffusion of In via metallization after thermal treatments at 300°C for 60 s [25]. The limited temperature stability could be caused by a high tendency of these metals to oxidation or a relatively low melting point Al (660°C) and high probability formations of Al droplets on the surface.

Table 3

Survey of literature data on bilayer ohmic contacts to n-type InN

Metal layers	Semiconductor hetero-structure	Layer thickness, nm	Donor concentration, cm^{-3}	Minimal resistivity, Ohm·cm^2	Treatment	Reference
Ti/Al	*n*+InN/GaAs	20/100/200	10^{20}	$1.2 \cdot 10^{-7}$	RTA 500°C, 15 s	[20]
Ti/Al	*n*+$In_{0,65}Al_{0,35}N$/GaAs	20/100/200	$8 \cdot 10^{18}$	$1.0 \cdot 10^{-4}$	RTA 450°C, 15 s	[20]
Ti/Al	*n*+$In_{0.75}Ga_{0,25}N$/GaAs	20/100/200	10^{19}	$2.0 \cdot 10^{-7}$	RTA 600°C, 15 s	[21]
Ti/Al	InN/GaN	20/100/100	10^{19}	$6.0 \cdot 10^{-5}$	RTA 500°C	[35]
Ti/Au	InN/AlN	100/200/ 1000/250	$2 \cdot 10^{18}$	$1.4 \cdot 10^{-7}$	non-annealed	[17]
Al/Au	InN/GaN/Al_2O_3	100/200/ 1000/220	$1.49 \cdot 10^{18}$	$1.9 \cdot 10^{-6}$	non-annealed	[17]
Ni/Au	InN/AlN/Al_2O_3	100/200/ 1000/200	$2.28 \cdot 10^{18}$	$1.0 \cdot 10^{-6}$	non-annealed	[17]
Ni/Ag	InN/GaN/Al_2O_3	–	—	$3.5 \cdot 10^{-2}$	TA 400°C, 30 min	[29]

Low values of the contact resistivity were achieved in [17] for non-annealed contacts. The authors associated this data to the existence of high-density surface charge in InN films, it is about $4.3 \cdot 10^{13}$ cm^{-2}. Probably, it is a crucial point in the formation of the ohmic contacts with Al, Ni, Ti contact layers immediately after the deposition of metallization on InN without subsequent annealing. However, in that work any structural research and temperature studies of electrical properties were not carried out thus the reliability and stability of such contacts is not completely investigated.

Barrier layer as part of multilayer contact metallization to *n*-InN

Modern researches of ohmic contacts argue about the feasibility and prospects of using multilayer contact structure [37]. As has been noted above, similar structure may consist of several metallic layers for various purposes.

The barrier layer is one of the most important part of multilayer contact metallization. It is generally a polycrystalline layer of refractory metal and alloy (Ni, Ti, Pt) [25, 26, 38, 39] or boride nanocrystalline layer of refractory metal (for example, TiB_2) [23].

Ti/Al/Ni/Au and Ti/Al/TiB2/Ti/Au ohmic contacts on *n*-type InN were compered [23]. These structures differ from each other only by the barrier layer. The minimum values of contact resistivity of $1.6 \cdot 10^{-6}$ and $6.0 \cdot 10^{-6}$ Ohm·cm^2 were obtained for the TiB_2-based and Ni-based ohmic contacts, respectively. However, significant differences could be observed examining AES depth profiles after RTA at 400°C (**Fig. 5**). According to Fig. 5, Ni layer is an unable to cope with its main purpose, which leads to a significant mass transfer between the metallization layers and the semiconductor. In contrast, the TiB_2-based ohmic contacts displayed thermal stability, suggesting that it is a better diffusion barrier than Ni. After RTA the TiB_2-based contact structure much better maintains layered homogeneity. Thus thermal stability and reliability of the investigated contacts were generally defined by the barrier layer properties.

Comparing the optimal values of the contact resistivity for structures using barrier layers and other contact metallization (**Fig. 6**), we notice low values of the contact resistivity in a wide range of doping concentration obtained for ohmic contacts with barrier layers.

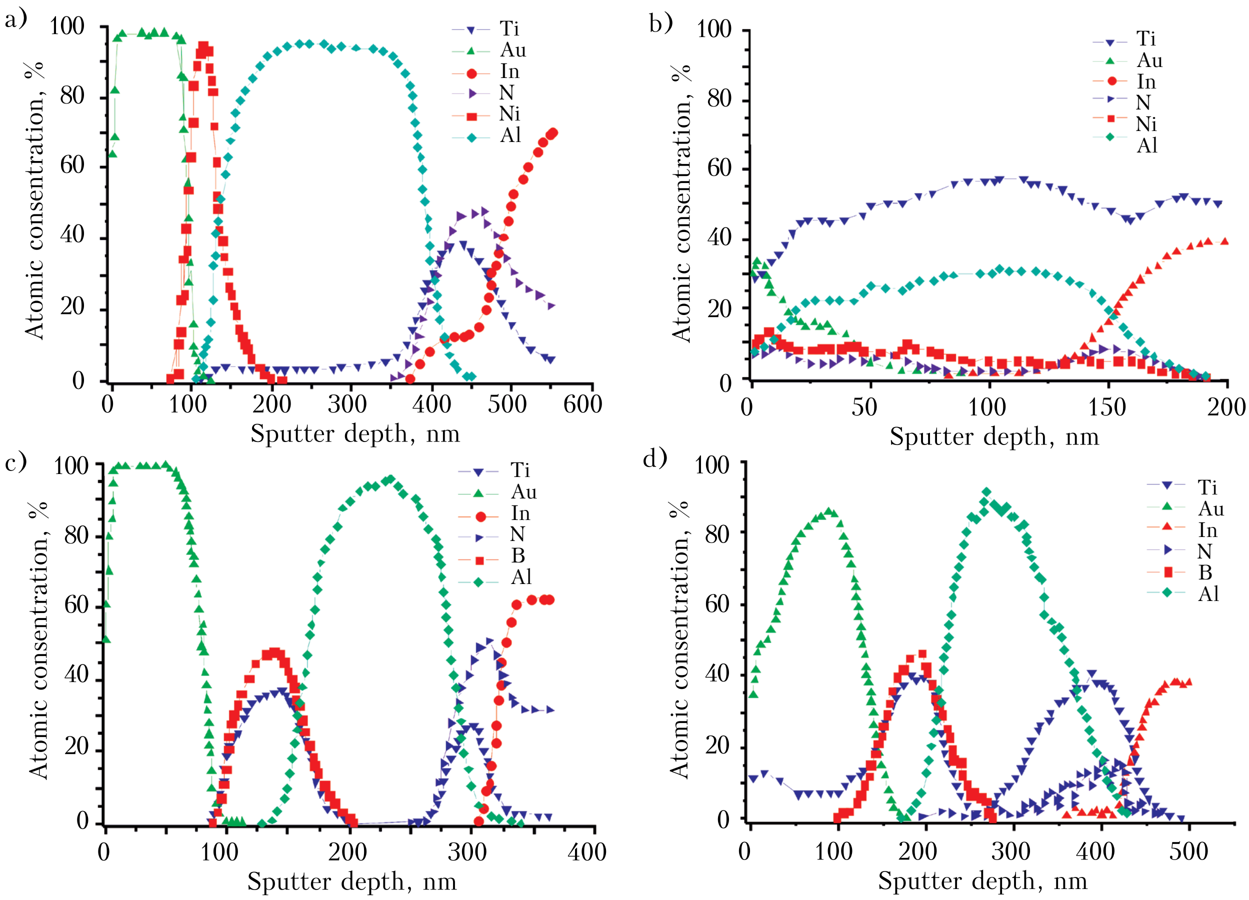

Fig. 5. AES depth profiles of multilayer metallization with barrier layers Ti/Al/Ni/Au (*a*, *b*) and Ti/Al/TiB_2/Au (*c*, *d*) as-deposited (*a*, *c*) and after RTA at 400°C (*b*, *d*) [23]

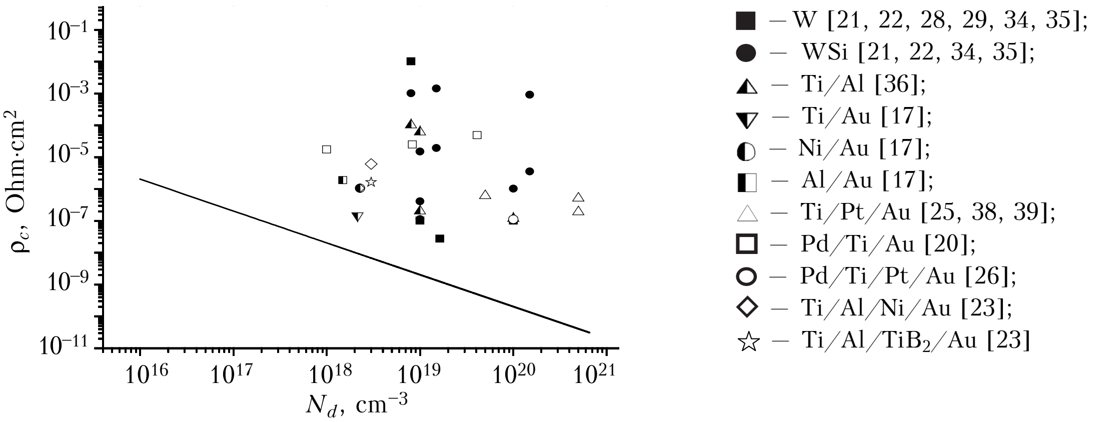

Fig. 6. Contact resistivity as a function of doping concentration: experimental data (dots) and theoretically calculated values of minimal contact resistivity (line)

Table 4

Survey of literature data on ohmic contacts to InAlN/GaN HEMTs

Metal layers	Semiconductor heterostructures*	Layer thickness, nm	Minimal resistivity	Treatment	Reference
Ti/Al/Ti/Au	$In_{0.15}Al_{0.85}N$(22.7)/GaN(2000)/SiC	20/100/45/55	430 Ohm·μ	RTA 850°C, 30 s	[41]
Ti/Au	InN(10)/InGaN(40)/GaN(20)/AlGaN/GaN(*n*-face)		27 Ohm·μ		[42]
Ti/Au	InAlN(2.5)/AlN(1.5)/GaN(200)/GaN(1600)/SiC		160 Ohm·μ		[43]
Ti/Al/Mo/Au	GaN(2)/$In_{0.134}Al_{0.866}N$(8)/AlN(1)/GaN(2000)/AlN(70)/SiC	16/64/30/50	300 Ohm·μ	RTA 860°C	[44]
Ti/Al/Ni/Au	$In_{0.17}Al_{0.83}N$(5)/AlN(1)/GaN(21)/AGalN(800)/SiC		410 Ohm·μ	RTA 830°C, 30 s	[46]
Ti/Al/Ni/Au	$In_{0.18}Al_{0.82}N$(9)/AlN(1)/GaN(2500μm)/Al_2O_3	30/160/40/50	$1.1\cdot10^{-7}$ Ohm·cm^2	RTA 600°C, $SiCl_4$ RIE	[46]
Mo/Al/Mo/Au	$In_{0.17}Al_{0.83}N$(5.6)/AlN(1)/GaN/6H-SiC	15/60/35/50	$7.8\cdot10^{-7}$ Ohm·cm^2	RTA 650°C 30 s, $SiCl_4$ RIE	[48]
Ti/Al/Ni/Au	$In_{0.17}Al_{0.83}N$(10.2)/GaN(50)/GaN(1900)/Al_2O_3		$2\cdot10^{-5}$ Ohm·cm^2	RTA 800°C 30 s, ICP-RIE	[49]
Ti/Al/Ni/Au	GaN(2.5)/$In_{0.17}Al_{0.83}N$(10.2)/GaN(50)/GaN(1900)/Al_2O_3		$3\cdot10^{-5}$ Ohm·cm^2	RTA 800°C 30 s, ICP-RIE**	[50]
Ti/Al/Ni/Au	GaN(2)/$In_{0.16}Al_{0.84}N$()/AlN(1)/GaN(3000)/AlN(300)/Al_2O_3	30/100/40/50	0.45 Ohm	RTA 800°C	[45]
Ti/Al/Au	$In_{0.18}Al_{0.82}N$(20)/AlN(1)/GaN(3600)/GaN(1000)/Al_2O_3	30/70/70	$5.28\cdot10^{-4}$ Ohm·cm^2	RTA 850°C	[26]
Ti/Al/Ni/Au	$In_{0.18}Al_{0.82}N$ (9)/AlN(1)/GaN(1300)/Si	25/200/40/100	$4.75\cdot10^{-6}$ Ohm·cm^2	RTA 800°C 60 s	[47]
Hf/Al/Ta	$In_{0.18}Al_{0.82}N$ (9)/AlN(1)/GaN(1300)/Si	15/200/20	$6.75\cdot10^{-6}$ Ohm·cm^2	RTA 600°C 60 s	[50]

* Layer thickness are presented in nanometers;
** ICP-RIE – Inductively Coupled Plasma Reactive Ion Etching.

Ohmic contacts to InAlN/GaN HEMTs

During the last decade the intensive research of InAlN/GaN heterostructure electrical parameters was conducted [27, 41—52], which is promising to create high electron mobility transistor (**HEMT**). Due to the better values of electron mobility and the possibility of high-density two-dimensional electron gas formation (2DEG), InAlN/GaN heterostructure is considered as an alternative to AlGaN/GaN using for creating the basis for stronger HEMTs. Since these transistors work with high current density, the ohmic contacts to them firs-of-all must withstand respective load. HEMT performance substantially depends on the parasitic resistance presence. Hence, as one of the priorities is reduction of the ohmic contact resistance.

One option for reducing the contact resistivity was the deposition of ohmic contacts onto thin 10 nm InN layer, which was epitaxial grown on GaN/InAlN heterostructure using graded $In_xGa_{1-x}N$ (40 nm, x = 0.01—0.26) [43]. In this way, due to the existence of high-density surface charges in InN films, the reduction of Ti/Au ohmic contact resistivity was achieved to 27 Ohm·m compared to 160 Ohm·m [44] for similar contacts without the InN top layer.

Another approach to reduction of contact resistance was using $SiCl_4$ reactive ion etching (**$SiCl_4$-RIE**) InAlN surface before metal deposition [45, 46]. In case of Ti/Al/Ni /Au, it is possible to significantly reduce the ohmic contact resistivity ($1.1 \cdot 10^{-7}$ Ohm·cm^2 after RTA at 600°C [47]) compering to similar contacts without using $SiCl_4$-RIE ($2 \cdot 10^{-5}$ Ohm·cm^2 after RTA at 800°C [47]). That was related to following $SiCl_4$-RIE advantages: the removing of the natural oxide from semiconductor surface; the removing of carbon impurities that accumulate on the surface during the epitaxial growth of InAlN by MOCVD; the thickness reduction of the potential barrier that allows electron tunneling through it.

Analyzing known contact metallization schemes to InAlN/GaN (**Table 4**), it is worth noting that the Ti/Al-based contact structures are widely spread. However, one of their distinctive feature is the possibility of contact inclusions or spikes formation after the high-temperature annealing which is required for the low-resistance ohmic contacts. The presence of such spikes was confirmed by transmission electron microscopy studies [27, 50]. According to the authors, Ti diffuse through InAlN layer, consequently TiN local inclusions were formed in GaN layer. The concentration of such inclusions exceed 10^8 cm^{-2} [27]. Whereas, that greatly affects the carrier transport mechanisms, since TiN acts as a carrier path leading between the metallization and the area of two-dimensional electron gas.

A sharp metal-semiconductor interface and avoidance significant interdiffusion between contacting layers were achieved by reduction RTA temperature to 600°C using metallization of refractory metals Hf/Al/Ta [51, 52].

Conclusion

In this study, the key issues for ohmic contact formation to InN-based materials have been reviewed, focusing on the cases of *n*-type InN and InAlN/GaN heterostructures. A critical analysis of the main literature results reported in the last three decades allowed identifying the most suitable metallization structures and optimal annealing conditions for ohmic contact formation.

Two main stages can be associated with the developing of the contact metallization to *n*-InN that might be separated by the period of the revaluation of semiconductor band gap and other essential parameters (effective electron mass, saturation velocity, mobility of electrons, etc.). In the first phase (90 years of XX century) interest in indium nitride was due to promising applications in the developing of some active elements for optoelectronics. Single-layer ohmic contacts based on W and WSi became the largest distribution during the first stage. Such type of metallization characterized by lowest optimal contact resistivity, however it requires high temperature annealing.

Since the beginning of the XXI century, indium nitride has been regarding as promising for high-speed semiconductor devices. Multi-layer metallization type with the barrier layers was used in case of InN. Thermal stability and reliability of whole metallization structure were generally defined by the barrier layer properties. The low contact resistance and superior thermal stability were achieved by using TiB_2 layers.

The mechanisms of current transport in the metal—InN structure aren't completely investigated due to the lack of information connected with temperature dependencies of contact resistivity and extended structural studies of semiconductor films.

The formation principles of ohmic contacts to InAlN/GaN heterostructures have the distinctive features. Using typical metallization based on Ti/Al mostly leads to the formation of contact inclusions or spikes that penetrate the InAlN layer. To avoid this in the current studies the following approaches were considered: using reactive ion etching InAlN surface before deposition ohmic contacts; search for alternative materials for contact metallization; using thin layers of refractory metals (Hf, Mo, Pd) to form a sharp boundary dividing «metal—semiconductor».

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ОМИЧЕСКИЕ КОНТАКТЫ К МАТЕРИАЛАМ НА ОСНОВЕ НИТРИДА ИНДИЯ

Рассмотрены ключевые моменты в формировании омических контактов к нитрид индиевых пленок, фокусируясь на n-InN и InAlN/GaN гетероструктурах. Детальный анализ исследований, проведенных за последние три десятилетия, позволяет определить основные принципы формирования подобных контактов. Приведены параметры контактов и оптимальные условия их достижения, рассмотрены различные типы металлизации и определены преимущества и недостатки каждого из них, учитывая основные требования, которым подобные контакты должны отвечать. Сделан акцент на перспективах использования многослойной металлизации с диффузионными барьерами. Рассмотрены общие подходы к формированию омических контактов к InAlN/GaN-гетероструктур.

Ключевые слова: омический контакт, нитрид индия, удельное контактное сопротивление, быстрая термическая обработка.

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ОМІЧНІ КОНТАКТИ ДО МАТЕРІАЛІВ НА ОСНОВІ НІТРИДУ ІНДІЮ

Нітрид індію, що є представником групи тринітридів, останнім часом викликає бурхливий інтерес серед дослідників з усього світу. Здебільшого це спричинено зростанням якості InN завдяки таким технологіям його вирощування, як металоорганічна газофазна епітаксія та молекулярно-пучкова епітаксія з плазмовою активацією азоту. Найнижче серед тринітридів значення ефективної маси електронів в поєднанні з високими значеннями швидкості насичення та рухливості електронів робить нітрид індію перспективним для розвитку високошвидкісної напівпровідникової електроніки. Використання $In_xGa_{1-x}N$ дозволяє перекрити весь видимий діапазон довжини хвиль, а $In_xAl_{1-x}N$ — діапазон довжини хвиль від інфрачервоного випромінювання до ультрафіолетового.

Критичною проблемою, що гальмує розвиток мікроелектроніки на основі InN, залишається складність створення омічного контакту до напівпровідникових плівок нітриду індію з високою густиною структурних дефектів. Подібні контакти мають задовольняти широкому спектру вимог. Насамперед, це технологічні вимоги до процесу їх виготовлення, до їх надійності та електрофізичних параметрів. Однак до тепер не було сформовано узагальненої картини фізичних процесів, що відбуваються в структурі «метал — InN» під час струмоперенесення, та не проведено огляд впливу технологічних умов на якість омічного контакту.

В даній роботі розглянуто ключові моменти в формуванні омічних контактів до нітрид-індієвих плівок, фокусуючись на гетероструктурах n-InN і InAlN/GaN. Детальний аналіз досліджень, проведених за останні три десятиліття, дозволив визначити основні принципи формування подібних контактів. Наведено параметри контактів та оптимальні умови їх досягнення, розглянуто різні типи металізації і визначено переваги та недоліки кожного з них, враховуючи основні вимоги, яким подібні контакти мають відповідати. Наголошено на перспективах використання багатошарової металізації з дифузійними бар'єрами. Розглянуто загальні підходи формування омічних контактів до InAlN/GaN-гетероструктур.

Ключові слова: омічний контакт, нітрид індію, питомий контактний опір, швидка термічна обробка.