Current transport through ohmic contacts to indium nitride with high defect density

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The temperature dependences of contact resistivity are measured for Pd/Ti/Au ohmic contacts toward indium nitride (with different doping level 2.0·10¹⁸ and 8.3·10¹⁸ cm⁻³) over the wide temperature range (4.2 — 380 K). The growing curves are obtained in the entire investigated temperature range for both doping level. They are explained within the mechanism of thermionic current flow through metal shunts associated with the so-called conducting dislocations. Good agreement between the theoretical and experimental dependences is obtained assuming that the flowing current is limited by total resistance of metal shunts. Moreover the effect of temperature dependence of metal resistivity on total contact resistivity was observed. The density of conducting dislocations obtained from the theory is coherent with the density of screw and edge dislocations obtained from X-ray diffraction investigation of the structure.

Keywords: ohmic contact; indium nitride, contact resistivity, current flow mechanism, rapid thermal annealing.

Получены нетипичные возрастающие температурные зависимости удельного сопротивления омических контактов Pd/Ti/Au к нитриду индия с разным уровнем легирования (2.0·10¹⁸ и 8.3·10¹⁸ см⁻³) в широком температурном интервале (4.2-380 К). Данные зависимости для разных уровней легирования объясняются в рамках механизма токопроводящими дислокациями, протекающими в тонкой приконтактной слой полупроводника. Хорошее согласование между теоретическими и экспериментальными зависимостями получено при учете того, что протекание тока ограничивается общим сопротивлением дуг. Рассматривается сравнение температурных зависимостей удельного сопротивления в случае осаждения на дислокационных атомов палладия или индия. При этом плотность проводящих дислокаций, рассчитанная из теории, хорошо согласуется с плотностями винтовых и краевых дислокаций, полученными из рентгенодифрактометрических исследований структуры.

Структурные дефекты в омических контактах до InN с высокой густотой структурных дефектов. П.О.Сай, Н.В.Сафриук, В.В.ШинкARENKO, П.Н.Брунков, В.Н.Имерих, С.В.Иванов

Открыты нетипичные температурные зависимости номинальных омических контактов Pd/Ti/Au к нитриду индия с различными уровнями легирования (2·10¹⁸ и 8·10¹⁸ см⁻³) в широком интервале температур (4.2-380 К). Даны зависимости для различных уровней легу-
1. Introduction

Indium nitride is one of the most intensely studied semiconductors among A5N group due to the appearance of more quality material in the last years. Currently InN films are grown by Metalorganic Vapour Phase Epitaxy (MOVPE) or Plasma-Activated Molecular Beam Epitaxy (PAMBE). This semiconductor is prospective for the development of high-speed devices, due to a set of following benefits [1]: low value of electron relative effective mass (0.04), the highest electron saturation velocity (3.4·10^7 cm/s) and mobility (3200 cm^2/V·s) among semiconductors of A5N group.

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According to the [2], one of the key problems is a creation of reliable ohmic contact to InN as an integral part of any semiconductor devices. This is due to the fact that the InN films are grown as heterostructures onto different substrate (GaN, Al2O3, GaAs, Si etc.). Therefore, relaxation of internal mechanical stresses caused by significant mismatch of the lattice parameters and thermal expansion coefficients of the InN films and substrate generates high structural defect density. In its turn structural defects effect on the mechanism of current flow through metal-semiconductor interface. Investigation of such mechanism in case of metal-InN is the main aim of present work. It is commonly known that for solving this problem the measuring temperature dependences of contact resistivity (ρo(T)) is required.

There are only two groups of researchers [3-5] who studied the properties of such ohmic contacts to n-InN in the 223 – 398 K temperature range [3,4] and in the 4.2 – 400 K temperature range [5]. They observed growing temperature dependences of resistance in ohmic contacts to heavily doped n-InN with doping level over 10^30 cm⁻³. In Reference [5] firstly a nanosized wire was made of heavily doped n-InN, then temperature dependences of the total resistance of nanowire and two identical contacts were measured. It is important to emphasize that the contact resistivity wasn’t determined separately in that case.

2. Experimental

In order to achieve the objectives the ohmic contacts were formed by the sequential vacuum deposition of Pd (30 nm)/Pt (60nm)/Au(100nm) onto the InN epitaxial films heated to 350°C. Two kinds of structures with different depth of InN layer (sample A – 0.6 and sample B – 2.5 μm) was grown on GaN (0.9 μm) buffer layer preliminarily formed on an Al2O3 by PAMBE. The free electron density in the InN films was 2.0·10^18 and 8.3·10^18 cm⁻³, respectively for A and B samples. Growing was monitored by reflected high-energy electron diffraction and laser refraction.

In the finally step of sample preparing the contact patterns were fabricated by the photolithography method with following metal etching and wafer cutting. In case of B sample, Rapid Thermal Annealing (RTA) was used at temperatures in the range 350 – 400°C with 2 min duration for improving metal-semiconductor contacts. No subsequent treatment of A sample was conducted. The contact resistivity was measured on planar test structures by the Transmission Line Method (TLM) before and after RTA. Measurements of ρo(T) were performed for obtained structures in the 4.2 – 300 K and 100 – 380 K ranges for A and B samples, respectively.

Structural parameters of semiconductor epitaxial films were determined by using a High-Resolution X-Ray Diffraction (HRXRD). Both the symmetric and asymmetric reflections of InN and GaN were analyzed. Dislocation densities (screw NS and edge NE), lateral (L∥) and vertical (L⊥) correlation length were analyzed by Williamson-Hall plots. Also the microstrain (ε⊥) was measured in the perpendicular plane to the growth direction from the experimentally obtained lattice parameters (c). Results of HRXRD investigation are shown in Table.

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Table. Comparing of structural parameters of samples

<table>
<thead>
<tr>
<th>Structural parameters of investigated samples</th>
<th>Number of sample and treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (no treatment)</td>
</tr>
<tr>
<td>Lattice parameter c, nm</td>
<td>0.57102</td>
</tr>
<tr>
<td>Vertical correlation length L, nm</td>
<td>670</td>
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<tr>
<td>Lateral correlation length l, nm</td>
<td>230</td>
</tr>
<tr>
<td>Microstrain $\varepsilon L^{-1}10^{-4}$, WH</td>
<td>4.68</td>
</tr>
<tr>
<td>Screw dislocation density $N_s 10^8$, cm$^{-2}$</td>
<td>2.30</td>
</tr>
<tr>
<td>Edge dislocation density $N_e 10^9$, cm$^{-2}$</td>
<td>34.70</td>
</tr>
</tbody>
</table>

Fig. 1. Histograms of $\rho_c$ distribution in case of B sample: before (top) and after (bottom) RTA 400°C.

Fig. 2. Temperature dependences of contact resistivity $\rho_c(T)$: dots — experimental data, line — theory.

3. Results and discussion

The ohmic contacts were formed to InN/GaN/Al$_2$O$_3$ semiconductor heterostructures with high structural defect density. As known, dislocation is the dominant structural defect in A$^0$N semiconductors films. It was particularly confirmed by HRXRD investigation (Tabl.). The screw dislocation density of both sample types is approximately equal and slightly increases after RTA 400°C (for B sample). In contrast to that, the density of edge dislocation is significantly higher in case of A sample. As will be proved below such high dislocation density effects on the mechanism of current flow through metal-semiconductor interface and complicates task of understanding it.

Obtained from TLM measurement value of contact resistivity is $(7.61 \pm 3.96) \times 10^{-6}$ and $(1.58 \pm 0.56) \times 10^{-4}$ $\Omega$cm$^2$ for A and B samples respectively. Higher value of $\rho_c$ of B sample was reduced to $(3.31 \pm 0.49) \times 10^{-5}$ $\Omega$cm$^2$ after RTA 400°C. Significantly that the width of $\rho_c$ spread greatly reduces after treatment as shown on the histograms of appropriate distribution (Fig. 1). According to the review [2], we obtained low $\rho_c$ values that are consistent with worldwide results.

As for $\rho_c(T)$ dependence, we obtained similar curve in case of B sample as for A sample in [6] (Fig. 2). Its behavior differs considerably from curves typical for ohmic Schottky contacts with classical current flow mechanisms. There are the tunneling (does not depend on temperature), the thermo-field and thermo-electron emission ($\rho_c$ decreases with temperature). In our
case, the contact resistivity grows with temperature for both sample types over the whole temperature range measured.

When performing theoretical modeling of the experimental $\rho_c(T)$ dependence we supposed that current flows through metal shunts associated with the so-called conducting dislocations.

To calculate contact resistivity $\rho_{ct}$ (for a contact of unit area) that is determined by supply of electrons from semiconductor to shunt ends, we apply the expressions from [6] that are true for a degenerate semiconductor:

$$\rho_{ct} = \frac{k}{q \pi N_D L_D^2 A (m / m_0) T \ln[1 + \exp(z + y_0) / kT]}.$$

(1)

Here $k$ is the Boltzmann constant, $q$ is elementary charge, $N_D$ is effective density of conducting dislocations, $L_D$ is Debye shielding length, $A$ is Richardson constant, $m$ is effective electron mass, $m_0$ is free electron mass, $y_0$ is non-dimensional (normalized to $kT$) contact potential.

Taking into account, that not the whole area is involved in process of current flow and the resistance of all metal shunts ($\rho_{sh}$) is connected in series with $\rho_{ct}$, the total resistivity of ohmic contact in a semiconductor with high dislocation density is

$$\rho_c = \rho_{ct} + \rho_{sh}.$$

(2)

Distinguish feature of current transport in our case is existence of potential wells rather than a potential barrier at the shunt end. It is result of following suggestion: both the edge effect (which leads to a considerable increase of the electric field strength) and the effect of the mirror image forces lead to a considerable reduction of the barrier height near a shunt. Thus, we consider non barrier mechanism of current flow though metal-semiconductor interface.

In contrast to modeling $\rho_c(T)$ for A sample in [6] where we suggested current flow through palladium shunts, there are indium shunts in case of B sample. Auger profiling and investigation of surface morphology confirmed that surface of semiconductors films of B sample was enriched in indium before metal deposition. In addition the temperature dependence of palladium metal shunts, behaves in the following way [6]: at $T = 0$ K, resistance of a normal metal is equal to the residual resistance. As temperature grows, the resistance increases as $T^6$ because of electron scattering by phonons. Then a transition region with growth $T_n$ is realized, with $n$ decreasing rapidly. And, at last, at $T \geq T_D$ ($T_D = 274$ K is the Debye temperature of palladium), $n = 1$, i.e., metal resistance grows linearly with temperature. Thus slow growth of $\rho_c(T)$ for A sample at low temperature we connected with effect of palladium $\rho_{sh}(T)$. As for A sample, the Debye temperature of indium is essential lower (129 K) and we observe only linear increasing of total contact resistivity over whole measured temperature range (100 – 380 K).

Other essential result lies in the fact that obtained from theory densities of conduction dislocation are $5.0 \times 10^9$ and $8.8 \times 10^9$ cm$^{-2}$ for A and B sample, respectively. These values well agree with densities of screw and edge dislocation (Table).

4. Conclusion

Low resistivity Au/Ti/Pd ohmic contacts were formed to indium nitride thin films with high defect density without any thermal annealing. Ability of using Rapid Thermal Annealing was also demonstrated for reduction both value of contact resistivity and its spread.

The thermionic current flow through metal shunts associated with the conducting dislocations was confirmed in case of ohmic contacts to lnN. Good agreement between the theoretical and experimental dependences of contact resistivity was obtained over wide temperature range (4.2 – 380 K). In addition, density of conduction dislocation obtained from theoretical measurement is close to densities of screw and edge dislocation determined by High-Resolution x-ray Diffraction.

References