**Ohmic contacts**

- **Common techniques to make ohmic contacts**
  - Choose metal so that its work function $F_{\text{metal}}$ is close to that of semiconductors $F_{\text{semi}}$ (thermal ionic)
  - Insert thin layer of narrow bandgap material between metal and semiconductor
  - Increase the doping level near the semiconductor surface as high as possible (tunneling assisted)

- **Ohmic contacts should be**
  - Low contact resistance ($< 10^{-6} \, \Omega \text{cm}^2$)
  - Thermally stable (does not degrade at elevated temperature or react with oxygen), which requires no phase change or no phase change leading to high resistance
  - Smooth morphology
  - Compatibility with the whole device process

- **Both semiconductors and metal sources should be CLEAN!**

*Michaelson, IBM J. of R&D, 1978*
Common Techniques for Ohmic contacts

(i) Ohmic contact by band alignment

- Usually for compound semiconductors, the ohmic contact by band alignment is hard to realize due to surface states and Fermi pinning. For p-type, the problem is caused by unavailability of metals with large enough work function.
- High n-type doping required for ohmic contacts to n-type semiconductors, which can also be realized by interfacial layer reaction chemistry.

\[
\phi_M < \chi + E_c - E_F = \phi_S
\]

For n-type semiconductor.
Reverse for p-type

(ii) Ohmic contact by high doping

- Electrons from conduction band can move very easily to the metal and vice versa by tunneling.

\[
\phi_B = \phi_S - \phi_M
\]

\[\phi_B = \text{band bending}\]
Ohmic on n-GaN

- Possible metals: Ag, Nb, Ti, Al, In, Ta, Cr
  - Ag: poor adhesion
  - Nb: extremely easy to oxidize thus difficult to process
  - Ti: formation of TiN (intermetallic) and high N vacancies in GaN -> good! But easy to oxidize… need a stable cap like Au
  - Al: formation of AlN (not intermetallic) and high N vacancies in GaN -> ok! Also easy to oxidize… Au cap is necessary
  - In: most popularly used for quick contacts
  - Ta: studied by Qiao et al. \(5.7 \times 10^{-7} \, \Omega \text{cm}^2\) on AlGaN/GaN (2001); but others could not reproduce the results
  - Others: also studied but not as good as the one below

- As deposited or alloy: generally alloyed unless doping near the surface is very high!

- Popular schemes: Ti/Al/Ni/Au
  - Ti/Al bilayer: formation of N vacancies, TiN, Al\(_3\)Ti (thermally very stable 😊); but ratio of Ti/Al has to be carefully controlled (~1/2.5 😞)
  - Add high conductive and protective layer of Au, but Au diffuses easily
  - Add Ni as diffusion barrier (decent, other metals were tried, Pd and Pt were worse)
  - State-of-art: \(0.1-0.2 \, \Omega \text{cm}^2\) (~ \(10^{-8} \, \Omega \text{cm}^2\))

FIG. 1. (a) Typical HREM image, and (b) enlarged image of the interfacial area near the AlGaN surface for the Ta/Ti/Al metal contacts to n-AlGaN/Au after annealing.

Lim et al, APL 78, 3797(2001)
Schottky contacts

- Schottky contacts are formed when
  - Doping in the semiconductor is not very high i.e. > ~5x10^{18} cm^{-3}
  - The metal work function is greater than the n-type semiconductor work function
  - The metal work function is lower than p-type semiconductor work function
  - Very high density of surface states “pinning” the Fermi level at the surface w.r.t. the conduction band (Example: GaAs)

\[ \phi_M > \chi + E_c - E_F = \phi_S \]

For n-type semiconductor and reverse for p-type

Electrons from conduction band or in the metal faces barrier to free movement, and tunneling is also not easy
Conduction mechanisms in Schottky contacts

- **Thermionic emission**
  - Electrons emit over the barrier
  - Low probability of direct tunneling
  - Valid for low doping ($N_D < ~ 10^{17} \text{ cm}^{-3}$)

- **Thermionic-field emission**
  - Electrons use thermal energy to tunnel through the thin barrier in the upper end of the conduction band
  - Valid for intermediate doping ($~ 10^{17} \text{ cm}^{-3} < N_D < ~ 10^{18} \text{ cm}^{-3}$)

- **Field emission**
  - Direct tunneling, as depletion region is very narrow
  - Valid for heavy doping ($N_D > ~ 10^{18} \text{ cm}^{-3}$); almost ohmic

- **Leakage current**
  - High probability of defect-assisted tunneling and simple conduction
  - Occurs in poor material/interface quality; dislocations
Thermionic emission current: Schottky diode

**I-V characteristics**

Typical I-V characteristics

**Schottky diode I-V equation:**

\[ J = J_0 \left( e^{qV/kT} - 1 \right) \]

where \( J_0 \) is the saturation current density given by

\[ J_0 = A^* T^2 \exp\left(-\frac{q\phi_{Bn}}{kT}\right) \]

\( T \) = temperature, \( A^* \) = effective Richardson’s constant

**Forward bias**

**Reverse bias**

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Schottky on n-GaN

- Experimentally shown very weak surface pinning
- Surface cleanness has been heavily investigated, however
  - External cleaning is generally sufficient to achieve decent Schottky
  - Leakage is largely due to dislocations
- Thermal stability is IMPORTANT
  - Ni does not react with GaN below ~ 600°C
  - Pd reacts with GaN at ~ 400-500°C
  - W and Rd ~ 600°C
- The higher the Schottky barrier, the lower the leakage current
- Using polarization in nitrides i.e. GaN/AlGaN/GaN structure, the Schottky barrier can be made larger

**Electrical properties of dislocations in MBE-grown n-GaN**
(Ed Yu --- UCSD)

- **Pure screw dislocations can be highly conductive in MBE-grown n-GaN:**

  - Screw: conducting, uncharged
  - Edge: nonconducting, \(-e\) charge
  - Mixed: nonconducting, \(-e\) charge

  ![Topography and current images](image)


- **Edge and mixed dislocations typically contain negative charge in dislocation core:**

  - Screw: conducting, uncharged
  - Edge: nonconducting, \(-e\) charge
  - Mixed: nonconducting, \(-e\) charge

  ![Graphs of potential and conductivity](image)

  - pure screw: \(b = <0001>\)
  - pure edge: \(b = 1/3<1120>\)
  - mixed: \(b = 1/3<11\bar{2}3>\)

Mitigation of dislocation-induced leakage currents in MBE n-GaN (Ed Yu, UCSD)

- **NaOH solution** • pH = 13.1 • T = 30° C
- V = 30V • I ~ 1-10mA • t = 1000s
- φ_b = 0.80±0.02V
  n = 1.74±0.01
- φ_b = 0.86±0.02V
  n = 1.13±0.02

Ohmic to p-GaN

- Similar techniques like ohmic to n-GaN have been tried, but:
  - \( r_C \approx 10^{-3} \ \Omega \text{cm}^2 \)
- P-GaN/Ni/Au annealed in air (\( \text{N}_2/\text{O}_2 \)) proved to be one of the best:
  - \( r_C \approx 10^{-6} \ \Omega \text{cm}^2 \)
- Why?
  - After annealing, new phases form: NiO, Ni-Ga-O with Au particles, GaN
  - NiO is p-semiconductor with high Ni vacancies
- Continuing challenges:
  - Transparency to visible and UV
  - Ohmic to p-AlGaN
  - Tunneling junction contacts

Ho et al. JAP 85, 4491 (1999)
Another Contact Metal for p-GaN

- The absence of a metal with a sufficiently high work function. The band gap of GaN is 3.4 eV, and the electron affinity is 4.1 eV, but metal work functions are typically ~ 5 eV
- The relatively low hole concentrations in p-GaN due to the deep ionization level of the Mg acceptor ~170 meV
- The tendency for the preferential loss of nitrogen from the GaN surface during processing, which may produce surface conversion to n-type conductivity.

- Palladium gallide creates Ga vacancies that reduce contact resistances
- Temperature and time of anneal also important
Schottky to p-GaN

The Origins of Leaky Characteristics of Schottky Diodes on p-GaN

L. S. Yu, L. Jia, D. Qiao, S. S. Lau, J. Li, J. Y. Lin, and H. X. Jiang

Abstract—The possible origins of leaky characteristics of Schottky barrier on p-GaN have been investigated. The as-grown samples did not show any electrical activities using Hall measurements. Ni diodes made on as-activated samples, either at 950 °C for 5 s or at 750 °C for 5 min exhibited quasi-ohmic behavior. Upon sequential etching of the sample to remove a surface layer of 150 Å, 1200 Å, and 5000 Å from the sample, the I–V behavior became rectifying. I–V–T measurements showed that the slopes of the lnI–V curves were independent of the temperature, indicative of a prominent component of carrier tunneling across the Schottky junction. C–V measurements at each etch-depth indicated a decreasing acceptor concentration from the surface. The highly doped (>1.7 × 10^{19} \text{ cm}^{-3}) and defective surface region (within the top 150 Å from surface) rendered the as-activated Schottky diodes quasi-ohmic in their I–V characteristics. The leaky I–V characteristics, often reported in the literature, was likely to be originated from the surface layer, which gives rise to carrier tunneling across the Schottky barrier. This highly doped/defective surface region, however, can play an important role in ohmic contact formation on p-GaN.

- Schottky (Ni) on as grown GaN:Mg (MOCVD) --- quasi-ohmic (higher Mg near the surface?)
- Schottky (Ni) on etched GaN:Mg --- rectifying (tunneling and defect-assisted tunneling still significant thus it is difficult to extract barrier height and Richardson constant from I–V)

Fig. 1. Configuration of Schottky diodes (a) top view and (b) cross section of etched sample.

<table>
<thead>
<tr>
<th>Etch-depth (Å)</th>
<th>0</th>
<th>150</th>
<th>1200</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>I–V curves</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quasi-ohmic</td>
<td>rectifying</td>
<td>rectifying</td>
<td>rectifying</td>
</tr>
<tr>
<td>N_A (×10^{19} \text{ cm}^{-3}) from surface</td>
<td>1.7±0.3</td>
<td>1.4±0.2</td>
<td>0.73±0.08</td>
<td></td>
</tr>
</tbody>
</table>

C–V
**Schottky contact characterization**

- **Current-Voltage (IV) measurements**

\[
J_0 = A* T^2 e^{-\frac{q\phi_{Bn}}{kT}} \cdot V_F \text{ vs. } J \text{ intercept gives } J_0 \text{ and } \phi_{Bn} = \frac{kT}{q} \ln\left(\frac{A* T^2}{J_0}\right)
\]

- **Capacitance-Voltage (CV) measurements**

\[
W = \sqrt{\frac{2\varepsilon_s}{qN_D} (\phi_{Bn} - V)} \Rightarrow C = \sqrt{\frac{q\varepsilon_s N_D}{2(\phi_{Bn} - V)}} \Rightarrow \frac{1}{C^2} \propto (\phi_{Bn} - V)
\]

- So the intercept of \(1/C^2\) vs. \(V\) gives the barrier height

- **Photoelectric measurements (by photon incident on the schottky contact; this is very accurate)**

- Photocurrent \(R\) is related to the barrier height as

\[
\sqrt{R} \sim hv - q\phi_{Bn} \quad \text{So the intercept gives the barrier height}
\]
Contact Metallization (Ti, Al, Ni, Au etc)
Metal Electron-Beam Evaporation System

Rapid Thermal Annealing System from 20 °C to 1000 °C in seconds
Ohmic contacts: n-type or undoped nitride

- Standard recipe for ohmic contact:
  - Ti/Al/Ti/Au or Ti/Al/Ni/Au deposition. Ti/Al thickness ratio is important
  - Annealing at 800 – 900 ºC for about 1 min for alloying. Alloying temperature and alloying time are important factors controlling contact resistance.

Since TiN and AlN are formed by reaction between the nitride layers and Ti or Al, N-vacancies are created, which can dope the contact region and create ohmic contact.

FIG. 4. Bright field TEM image from the interface after 700 ºC annealing. The AlGaN layer is almost unreacted, and the thin interfacial layer is clearly visible. A site of possible local metal penetration into the AlGaN can also be seen. Au is present close to the interface, but apparently not in the interface phases.
Specific contact resistivity and sheet resistance

For any semiconductor device there are two main resistances:
• Contact resistance
• Semiconductor resistance

Product of contact resistance $R_c$ and area $A$ is called specific contact resistivity $\rho_c$:

$$\rho_c = \frac{1}{\frac{\partial J}{\partial V}_{V=0}} \quad (\Omega \cdot \text{cm}^2)$$

(Can also be expressed in terms of $\Omega \cdot \text{mm}$)

Semiconductor layer resistivity $\rho$:

$$\rho = \frac{1}{e n \mu} \quad (\Omega \cdot \text{cm})$$

Sometimes semiconductor resistance is expressed in terms of sheet resistance $\rho_{sh}$

$$\rho_{sh} = \frac{1}{t(e n \mu)} = \frac{\rho}{t} \quad (\Omega/\square)$$

The total semiconductor resistance is then given by

$$R_s = \frac{1}{A} \int_0^d \rho \, dx = \frac{\rho d}{Z t} \quad (\Omega)$$
Ohmic contact characterization: 
Transmission line method (TLM)

\[ \frac{dI}{dx} = -\frac{V(x)Z}{\rho_c} \]
\[ \frac{dV}{dx} = -\frac{I\rho_s}{Zt} = -\frac{I\rho_{sh}}{Z} \]

\[ \Rightarrow \frac{d^2I}{dx^2} = \frac{I(x)}{L_T^2}, \text{ where } L_T = \sqrt{\frac{\rho_c}{\rho_{sh}}} \]

is called the transfer length.

The solution for \( I(x) \) is given as:

\[ I(x) = Ae^{x/L_T} + Be^{-x/L_T} \]

Now putting the boundary condition \( I(x = L) = 0 \), and finding the solution for \( V(x) \), we can find the contact resistance as the ratio of the input voltage and input current as:

\[ R_C = \frac{V(x = 0)}{I(x = 0)} \]
Transmission line method (TLM) II

The contact resistance $R_c$ is then given by: 

$$R_c = \frac{\rho_c}{ZL_T} \coth \left( \frac{L}{L_T} \right)$$

For $L >> L_T$, we have, 

$$R_c = \frac{\rho_c}{ZL_T}$$

When the following conditions are further satisfied, $d << Z$ and $t << L_T$ (to avoid current spreading in the sides or into the film), 

Then, 

$$R_{Tot} = 2R_c + R_s = 2R_c + \frac{\rho_{sh} d}{Z}$$

Putting $R_{tot} = 0$, and using the relation $\rho_c = R_c L_T Z$, we have, 

$$d(R_T = 0) = -2L_T$$. So, the transfer length can be found from the intercept of the total resistance on the x-axis.

Note that the contact resistivity is not given by the product of the contact resistance and the total contact area, but by the product of contact resistance, width $Z$, and transfer length $L_T$. 

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Measurement technique

Typical measurement set up

What is wrong in this measurement?

Plot of total resistance vs. distance

Slope = \( \rho_{sh}/Z \)

\[ Y = 14.51607 + 1.13839X \]
\[ R_{c} = 7.258 \Omega \]
\[ L_{T} = 6.373 \mu m \]
\[ \rho_{c} = 6.93 \times 10^{-5} \Omega \cdot \text{cm}^{2} \]
\[ R_{sh} = 170.7 \Omega/\text{sq} \]