Ohmic contact engineering in few-layer Black Phosphorus

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Context

• New materials for different applications than silicon-based electronics

• 2D semiconducting materials for multifunctional devices

X. Ling et al., PNAS 112 (2015) 4253

• Perspective of black phosphorus field-effect transistors

• What is the best contacting metal to black phosphorus?
Outline

• Black Phosphorus presentation

• Metal-Semiconductor contact

• Electrical contact engineering

• Field-Effect transistors

• Field-effect transport measurements

• Summary and discussion
Black Phosphorus Presentation

- Layered & puckered structure
- Intrinsic P-doped semiconductor
- Direct band gap from 0.3 eV to 1-2 eV, tunable with strain and layer number
- Highly anisotropic & reactive material

Metal-Semiconductor Contact

- Holes accumulation at the interface
- Ohmic contact
- Drift-Diffusion current
Metal-Semiconductor Contact

- Schottky barrier for holes at the interface
- Schottky contact
- Thermoionic and tunnel current
Electrical contact engineering

- 3 different metals: Chromium, Titanium, Nickel
  \[ \Phi_{Cr} \approx 4.5 \text{ eV}, \Phi_{Ti} \approx 4.3 \text{ eV}, \Phi_{Ni} \approx 5.0 \text{ eV}, \Phi_{bP} \approx 4.5 \text{ eV} \] (Y. Cai et al., Sci. Rep. 4 (2014) 6677)

- Needle-shaped flakes for inter-digitated contacts geometry
Measurement setup

- 2-probe resistance measurements for Transfer Length Method (TLM)

\[ 2 \times R_C = R_{2-probe} - R_{4-probe} \]

- 4-probe resistance measurements for comparison with TLM

- Room temperature and low temperature measurements in a cryostat at liquid He temperature (4.2 K)
Transfer Length Method

\[
R_{2-probe} = \frac{R_S}{W} L + 2R_C
\]

- \(R_c\): Contact resistance (\(\Omega\))
- \(R_s\): Sheet resistance (\(\Omega/\square\))
- \(W\): Channel width (m)
- \(L\): Channel length (m)

Channel resistivity \(\rho_S = R_s \frac{W \times t}{L}\)

Contact resistivity \(\rho_C = R_C A_C\)
I-V curves in 2-probe configuration

For the three contacting metals:

- Ohmic-like contact between -1 mV and 1 mV
- $R_{2\text{-probe}}$ increases with L as expected
- $R_{2\text{-probe}\mid \text{Room T}} < R_{2\text{-probe}\mid \text{Low T}}$
The intercept and the slope are extracted to estimate $R_c$ and $R_s$.

The slope is given by $R_s/W$. 

$R_{2-probe} = 2R_c$. 

Ni contacts: 
- Room T
- Low T
- Fit Room T
- Fit Low T

Ti contacts: 
- Room T
- Low T
- Fit Room T
- Fit Low T

Cr contacts: 
- Room T
- Low T
- Fit Room T
- Fit Low T
### TLM Results

\[ \Phi_{\text{Cr}} \approx 4.5 \text{ eV}, \quad \Phi_{\text{Ti}} \approx 4.3 \text{ eV}, \quad \Phi_{\text{Ni}} \approx 5.0 \text{ eV}, \quad \Phi_{\text{bP}} \approx 4.5 \text{ eV} \]

<table>
<thead>
<tr>
<th></th>
<th>( R_s/W ) (k(\Omega/\mu\text{m} ))</th>
<th>( R_s ) (k(\Omega/\square ))</th>
<th>( R_c ) (k(\Omega ))</th>
<th>( \rho_c ) (k(\Omega \cdot \mu\text{m}^2 ))</th>
<th>( R_c = (R_{2\text{-probe}} - R_{4\text{-probe}})/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>4.43x + 0.75</td>
<td>4.43 ± 0.11</td>
<td>8.86</td>
<td>0.38 ± 0.12</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W = 2 \mu\text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>4.56x + 0.97</td>
<td>4.56 ± 0.23</td>
<td>5.93</td>
<td>0.49 ± 0.25</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W = 1.3 \mu\text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>5.83x + 0.48</td>
<td>5.83 ± 0.11</td>
<td>5.25</td>
<td>0.24 ± 0.07</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W = 0.9 \mu\text{m} )</td>
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</tbody>
</table>

### Low Temperature

<table>
<thead>
<tr>
<th></th>
<th>( R_s/W ) (k(\Omega/\mu\text{m} ))</th>
<th>( R_s ) (k(\Omega/\square ))</th>
<th>( R_c ) (k(\Omega ))</th>
<th>( \rho_c ) (k(\Omega \cdot \mu\text{m}^2 ))</th>
<th>( R_c = (R_{2\text{-probe}} - R_{4\text{-probe}})/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>10.59x + 2.35</td>
<td>10.59 ± 0.22</td>
<td>21.20</td>
<td>1.18 ± 0.40</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W = 2 \mu\text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>6.72x + 2.09</td>
<td>6.72 ± 0.74</td>
<td>8.75</td>
<td>1.05 ± 0.80</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W = 1.3 \mu\text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>7.63x + 2.15</td>
<td>7.63 ± 0.61</td>
<td>6.87</td>
<td>1.08 ± 0.43</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Field-Effect Transistor

With P-doped semiconductor:

- $V_g < 0$: holes accumulation in the channel and easier hole injection at the contact
- $V_g > 0$: depletion and inversion in the channel, easier electron injection at the contact

Field-Effect Measurements

- $I_{SD}$ vs $V_G$ characteristics

S. Das et al., ACS Nano 8 (2014) 11730
Field-Effect Mobility

4-probe conductance (G) measurement:

- Mobility of the semiconductor
- No contribution from the contacts

\[
\mu_{FE} = \frac{dG}{dV_g} \frac{L}{W} \frac{1}{C_{OX}}
\]

L : gate length (m)
W : gate width (m)
C_{OX} : Oxide capacitance per unit of area (F/m²)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature</th>
<th>( \mu_{FE} ) from G vs Vg (cm²/(V.s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>Room Temperature</td>
<td>160,11</td>
</tr>
<tr>
<td>Ti</td>
<td>Low Temperature</td>
<td>563,37</td>
</tr>
<tr>
<td>Cr</td>
<td>Room Temperature</td>
<td>39,21</td>
</tr>
<tr>
<td>Cr</td>
<td>Low Temperature</td>
<td>-</td>
</tr>
<tr>
<td>Ni</td>
<td>Room Temperature</td>
<td>223,31</td>
</tr>
<tr>
<td>Ni</td>
<td>Low Temperature</td>
<td>1252,16</td>
</tr>
</tbody>
</table>
Summary

• Ohmic contact gives lower contact resistance:
  - More scattering in Titanium datas
  - Nickel has the lowest contact resistivity

• In this framework Nickel gives the best results with a good ohmic contact

• More scattering in Titanium datas and more defects, the one to avoid

• All our FETs displayed unipolar behaviour

• Good mobility values according to what is found in the literature
Outlooks

• Extraction of Schottky barrier height to see the real nature of the contact

• Simulations of the interface to theoretically confirm those results

• Try with other metals to see if we can find better than Nickel

• Ambipolar behaviour is expected for thinner flakes (close to monolayer)
Acknowledgement
Thank you for your attention
Field-Effect Measurements

- **Field-effect mobility**

\[
\mu_{FE} = \frac{dI_{SD}}{dV_g} \frac{L}{W \cdot C_{OX} \cdot V_{SD}} \frac{1}{V_{SD}}
\]

\[
\mu_{FE} = \frac{dG}{dV_g} \frac{L}{W \cdot C_{OX}} \frac{1}{V_{SD}}
\]

<table>
<thead>
<tr>
<th>Extracted $\mu_{FE}$ (cm$^2$/V.s)</th>
<th>$I_{SD}$ vs $V_g$</th>
<th>$G$ vs $V_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti Room Temperature</td>
<td>61.51</td>
<td>160.11</td>
</tr>
<tr>
<td>Ti Low Temperature</td>
<td>216.43</td>
<td>563.37</td>
</tr>
<tr>
<td>Cr Room Temperature</td>
<td>23.46</td>
<td>39.21</td>
</tr>
<tr>
<td>Cr Low Temperature</td>
<td>101.46</td>
<td>-</td>
</tr>
<tr>
<td>Ni Room Temperature</td>
<td>78.30</td>
<td>223.51</td>
</tr>
<tr>
<td>Ni Low Temperature</td>
<td>391.17</td>
<td>1252.16</td>
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