Metal-Semiconductor Contacts

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Outline

• **Metal-semiconductor contacts**
  – Energy band alignment
  – Fermi-level pinning
  – Current transport and barrier height extraction
  – Measurement of $R_c$ and $\rho_c$

• **Contact resistance in emerging materials**
  – Germanium
  – $\text{MoS}_2$
Outline

• Metal-semiconductor contacts
  – Energy band alignment
  – Fermi-level pinning
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• Contact resistance in emerging materials
  – Germanium
  – MoS$_2$
Metal-semiconductor Band Alignment

- In equilibrium Fermi-levels align
- Depletion-mode contact
Try this yourself

- What kind of a contact is this?
Schottky-Mott Rule

- $\phi_B$ reflects the mismatch in energy position of majority carrier band edge of the semiconductor and the metal Fermi level at the interface.
Deviation from Ideal (Schottky-Mott)

- Experimental vs measured SBH on Si
Interface States: Fermi-level Pinning

Charge at the interface due to electronic states in the bandgap

\[ Q_M + Q_{SC} + Q_{SS} = 0 \]

\[ \Phi_B = S(\Phi_M - \chi_S) + (1 - S)(\Phi_{CNL}) \]

\[ S = \frac{\partial \Phi_B}{\partial \Phi_M} \]

\[ D_S = \frac{(1 - S)\varepsilon_i}{S\delta_i} \]

- Interface states → dipole → interfacial layer of atomic dimensions
- \( \Phi_{CNL} \) energy level below which all states must be filled to ensure charge neutrality, measured from VBM
- \( S \) depends on \( D_s \) and \( \delta_i \)
Origin of Interface States: Model 1 - Unified Defect Model by Spicer

- Surface states created by dangling bonds of covalent semiconductor
- Fermi level pins at defect levels for sub/few monolayer metal coverage
Origin of Interface States: Model 2-
Metal Induced Gap States by Heine


- Interface states → tails of the metal wave functions
- Length of the tail ~ a few lattice constants, depends on complex energy band structure of semiconductor
- Deviation from local charge neutrality results in "metallic" screening by MIGS → Fermi-level pinning


- Gap states come from valence band and conduction band states
- Charge neutrality requires filling of valence band like states and empty conduction band states
- Cross-over point → Branch point → MIGS DOS is minimum and $E_F$ is pinned here

$$E_B = \frac{1}{2}(E_V + E_C)$$

$$E_V = E_N - \frac{1}{3} \Delta_{so}$$
Current transport in Contacts

(a) Thermionic emission

(b) Thermionic-field emission

(c) Field emission.
Contact Resistance and Resistivity

- Specific contact resistivity is a key parameter to describe contact performance

\[ V = V_{\text{bulk}} + 2V_{\text{contact}} = (R_{\text{bulk}} + 2R_{\text{contact}})I \]

\[ R_{\text{bulk}} = \frac{dV_{\text{bulk}}}{dI} = \frac{\rho l}{A} \]  \( \rightarrow \) Bulk resistivity

\[ R_{\text{contact}} = \frac{dV_{\text{contact}}}{dI} = \frac{\rho_c}{A} \]  \( \rightarrow \) Specific Contact Resistivity

\[ \rho_c = \lim_{V \to 0} \left( \frac{dV_{\text{contact}}}{dJ} \right) \ \Omega \ cm^2 \]

\[ J = \frac{v_{\text{metal}} - v_{\text{semicond}}}{\rho_c} \]
Thermionic Emission: Schottky Contact

- Specific contact resistivity independent of doping

\[ J_S = A^* T^2 \exp\left(\frac{-2\phi_B}{kT}\right)\left(e^{qV/kT} - 1\right) \]

\[ \rho_c = \frac{k}{qA^* T} \exp\left(\frac{2\phi_B}{kT}\right) = \frac{kT}{qJ_s} \]
Field Emission (Tunneling): Ohmic contact

\[ X_d = \sqrt{\frac{2 K \varepsilon_o \phi_i}{q N_d}} \]

\[ N_{d_{\text{min}}} \approx \frac{2 K \varepsilon_o \phi_i}{q X_d^2} \approx 6.2 \times 10^{19} \text{cm}^{-3} \quad \text{for} \quad X_d = 2.5 \text{nm} \]

\[ J_{sm} = \frac{A^* T}{k} \int F_s P(E)(1 - F_m)dE \]

\[ P(E) \sim \exp \left( -\frac{2\Phi_B}{\hbar} \sqrt{\frac{\varepsilon_m^*}{N}} \right) \]

\[ J_{sm} \propto \exp \left[ -2x_d \sqrt{2m^* (q\phi_B - qV)/\hbar^2} \right] \]

\[ \rho_c = \rho_{co} \exp \left( \frac{2\phi_B}{\hbar} \sqrt{\frac{\varepsilon_m^*}{N}} \right) \quad \text{ohm}^{-1} \text{cm}^2 \]
Contact resistivity on Si
How do you measure $\varphi_B$?

$$J = A^* T^2 \exp\left(-e \frac{\varphi_{Bn}}{kT}\right) \left(\exp\left(\frac{enV_a}{kT}\right) - 1\right), \quad A^* = \frac{4\pi e m_n^* k^2}{h^3}$$

- I-V measurement in a low doped Schottky diode
How do you measure $\varphi_B$?

• Reverse bias C-V curves give $\varphi_B$ and doping $N_d$

\[
\left( \frac{1}{C'} \right)^2 = \frac{2(V_{bi} + V_R)}{e \varepsilon_S N_d}, \quad V_{bi} = \phi_{B0} - \phi_n, \quad \phi_n = \frac{kT}{e} \ln \left( \frac{N_C}{N_d} \right)
\]
How do we measure $R_c$ and $\rho_c$?

- If current density was uniform then $\rho_c$ is contact resistance/A
- In practice $\Rightarrow$ J is non uniform due to current crowding
- Need a more accurate model
Model for Contact Resistance

- \( v_m(x,y,z) \rightarrow \text{Metal potential} \)
- \( v(x,y,z) \rightarrow \text{Semiconductor potential} \)
- Poisson and carrier continuity eqns
- Effect of minority carriers is neglected
  - Neglecting the semiconductor depletion width
  - Only need to solve the majority carrier continuity eqn in the semiconductor region under the contact
- Assume majority carrier density is the same as the active doping density
- Metal conductivity >> semiconductor conductivity \( \rightarrow v_m \)
  is constant along entire interface \( \rightarrow \) Only need to solve for \( v(x,y,z) \)
3D Model - Equations

\[ J = J(v_m - v) = J(v_{ms}) \]

\[ J(v_{ms}) = J(0) + \frac{\partial J(v_{ms})}{\partial v_{ms}} \bigg|_{v_{ms}=0} v_{ms} + \frac{1}{2} \frac{\partial^2 J(v_{ms})}{\partial^2 v_{ms}} \bigg|_{v_{ms}=0} v_{ms}^2 + \cdots \]

\[ J = \frac{v_{ms}}{\rho_c} \]

\[ \rho_c = \left( \frac{\partial J(v_{ms})}{\partial v_{ms}} \right)^{-1} \bigg|_{v_{ms}=0} \]

\[ \sigma = \sigma(x, y, z) = qN(x, y, z) \mu(x, y, z) \]

\[ \nabla \cdot J = \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z} = 0 \]

\[ J = -\sigma E = \sigma \nabla V \]

\[ \nabla \cdot \sigma \nabla V = 0 \]

\[ I_{tot} = -\int J \cdot dA \]

Difference in Fermi potentials of majority carriers

Finite resistance seen by infinitesimal current crossing the interface for infinitesimal applied V
Assumptions

\[ \sigma = \sigma(Z), \quad R_s = \left( \int \sigma(z) dz \right)^{-1} \]

\[ V = V(x, y) = R_s \int_z \sigma(z) v(x, y, z) dz. \]

\[ \nabla_t \equiv a_x \frac{\partial}{\partial x} + a_y \frac{\partial}{\partial y}. \quad \nabla^2_t = \frac{\partial^2}{\partial^2 x} + \frac{\partial^2}{\partial^2 y}. \]

Sheet Resistance of the semiconductor

Conductivity weighted average potential

Transverse gradient and Laplacian operators
2D Model

\[ \nabla \cdot J = \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z} = 0 \]

\[ J = -\sigma \nabla v \]

\[ \int_{z} \rightarrow -\nabla_t \cdot \sigma(z) \nabla_t v(x, y, z) + \frac{\partial J_z}{\partial z} = 0. \]

Integrating along \( z \)

\[ -R_s^{-1} \nabla_t^2 V(x, y) = J_z(0) - J_z(z_j) \]

\[ \nabla_t^2 V(x, y) = \frac{R_s}{\rho_c} \left[ V(x, y) \Gamma - v_m(x, y, 0) \right] \]

\[ \Gamma = \frac{v(x, y, 0)}{V(x, y)} \]

Assuming \( v_m \) to be constant and 0

Close to 1 for shallow junctions

Helmholtz equation, Under the contact

Laplace equation, Not under the contact

\[ \nabla_t^2 V = \frac{V}{l_t^2} \]

\[ l_t = \sqrt{\rho_c / R_s} \]
2D Simplified to a 1D Model

- Neglecting y-axis variation

\[ \nabla^2 V = \frac{V}{l_t^2} \rightarrow \frac{\nabla^2 V(x)}{\partial^2 x} = \frac{V(x)}{l_t^2} \]

- V=V_i at x=0 and dV/dx=0 at x=l

\[ V(x) = V_i \frac{\cosh \left( \frac{l - x}{l_t} \right)}{\cosh \left( \frac{l}{l_t} \right)} \]

\[ I_{tot} = \frac{W}{R_s} \frac{\partial V}{\partial x} \Bigg|_{x=0} \]

\[ I_{tot} = \frac{WV_i}{R_s l_t} \frac{1}{\coth \left( \frac{l}{l_t} \right)} \]

\[ I_{tot} = -\int J \cdot dA \]
\[ \rho_c = \frac{R_c}{A}. \]

- \( R_c \) approaches \( \rho_c A \) as \( l \) becomes less than \( l_t \)
- Potential across the semiconductor is uniform
- Current entering the contact is uniform
- Macroscopic definition
1D Transmission line model

- $R_c$ is dependent on contact size, structure layout besides semiconductor doping and $\rho_c$
- $\rho_c$ is a fundamental quantity governed by the interface

1D Transmission Line Model (Distributed $\rho_c$ and $R_s$)
1D Transmission line model

\[ I(x) = I_1 \exp \left( -\frac{x}{\sqrt{\rho_c/R_s}} \right) = I_1 \exp \left( -x/l_t \right) \]

\[ l_t = \sqrt{\rho_c/R_s} \]

- Current density drops exponentially from leading edge to trailing edge of the contact
- \( l_t \) is the characteristic length over which current drops by 63%
1D Transmission line model

For $d << l_t$, or large $l_t$

$$R_c = R_f = V_f / I_1 = \frac{\sqrt{R_s \rho_c}}{w} \coth\left(\frac{d}{l_t}\right)$$

Similarly for $d >> l_t$

$$R_f \approx \frac{\rho_c}{wd} \quad \text{As if you have uniform current density through the entire contact}$$

Recall,

$$I_1 = \frac{WV_i}{R_s l_t} \left(\frac{1}{\coth\left(\frac{l}{l_t}\right)}\right)$$

$$R_f \approx \frac{\rho_c}{wl_t} \quad \text{As if you have uniform current density through an effective area of } wl_t$$
1D Transmission Line Model

\[ R_f \approx \frac{\rho_c}{ZL} \quad R_f \approx \frac{\rho_c}{Zl_t} \]

- \( R_c \) plateau determined by \( L_t \) value for given \( \rho_c \)
Measurement of $R_c$ and $\rho_c$

\[
V_{24} = V_f + IR_{Si} + V_f \\
R_t = \frac{V_{24}}{I} = 2R_f + R_s l_s/w
\]

- Transmission line tap resistor
Measurement of $R_c$ and $\rho_c$

Value of $R_f$ ($R_c$) is small compared to $R_s$

Measurement of $R_t$ needs to be accurate

$$R_t = \frac{V_{24}}{I} = 2R_f + R_s\frac{l_s}{w}$$
TLM Method

- For $L \gg L_T$, x-intercept gives $L_T$ value

$$R_T = \frac{R_{sh}d}{Z} + 2R_c \approx \frac{R_{sh}}{Z} (d + 2L_T)$$
Cross-bridge Kelvin Resistor

- Assumes uniform current density through the entire contact area
Limitations of 1D Model

- 2D current flow is not accounted for
- Overestimation of $\rho_c$ - does not scale with area
- Need accurate 2D/3D current flow simulations
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• Contact resistance in emerging materials
  – Germanium
  – $\text{MoS}_2$
Engineering innovation has sustained Moore’s law

- Strain
- Hi-K/Metal Gate
- FinFET/Trigate
What’s next for Moore’s law?

High Mobility/Injection Velocity

\[ I_d = \frac{\mu C_{ox}}{L_{eff}} (V_g - V_t)^\alpha \]

- Mobility enhancement using alternate channel materials, strain, wafer orientation

- Ge is a single material CMOS solution
- Integral part of Si foundries

Lubow et al., APL 96 122105 (2010)

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>InGaAs</th>
<th>InAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility (electrons) in cm² V⁻¹ s⁻¹</td>
<td>1350</td>
<td>3600</td>
<td>8000</td>
<td>11 200</td>
<td>30 000</td>
</tr>
<tr>
<td>Mobility (holes) in cm² V⁻¹ s⁻¹</td>
<td>480</td>
<td>1800</td>
<td>300</td>
<td>300</td>
<td>450</td>
</tr>
</tbody>
</table>

Intel HiK-MG Ge device

Intel Developer Forum, Sept. 2011
What’s next for Moore’s law?

Improved Electrostatics/Sub-\(V_t\) Slope

\[ I_d = \mu C_{ox} / L_{eff} \left( V_g - V_t \right)^\alpha \]

Lower \(L_{eff}\) at same \(V_t\), or lower \(V_t\) at same \(L_{eff}\)

- Scaled FinFETs
- GAA FETs
- Tunnel FETs
- Ultra thin (2D) materials: \(\text{MoS}_2, \text{WSe}_2\)
• Contribution of contact resistance to overall parasitic series resistance is increasing with scaling
• $L_{\text{contact}}$ scales faster than $L_{\text{gate}}$

• Aggressive reduction of Contact-to-S/D specific contact resistance ($\rho_c$) needed
Metal-semiconductor contacts

Fermi level pinning is the “lack of barrier height modulation with metal work function” due to
- Either large density of “intrinsic” states: e.g. point defects on semiconductor surface
- Or “extrinsic” Metal-Induced-Gap-States (MIGS)

\[
\Phi_B = S(\phi_M - \chi_s) + (1 - S)(E_C - E_{CNL})
\]

\[
\rho_c \propto \exp\left(\frac{4\pi\Phi_B}{qh} \sqrt{\frac{m^* \varepsilon}{N_{surf}}} \right)
\]
Ge Transistor Contacts

- **N⁺ Silicon S/D**
  - N-type barrier height is high (NiSi, NiPtSi)

- **N⁺ Si:C S/D (higher mobility)**
  - N-type barrier height is high (NiSi, NiPtSi)
  - Effective doping is less vs Si

- **N⁺ Ge S/D (higher mobility)**
  - N-type barrier height is high
    - Fermi level pinning near VB
  - Low dopant activation (~5e19 cm⁻³)
Solution: MIS Contacts

Metal-Interfacial Layer-Semiconductor

\[ S: \text{pinning factor} \]
- S=1 Ideal surface, No pinning
- S=0 complete pinning

\[ \rho_c: \text{Specific contact resistivity} \]
- \( \rho_c \) depends on \( \phi_{B,eff} \)
- \( \rho_c \) depends on \( \Delta E_c \)

\[ \varepsilon_{IL} \uparrow \]
\[ E_{gIL} \uparrow \]
\[ \text{thickness } t \text{ of IL } \uparrow \]
\[ \rho_{\Delta E_c} \downarrow \]
\[ \text{thickness } t \text{ of IL } \downarrow \]

Jenny Hu et al. MRS Bulletin 2011
MIS vs Silicide

- MIS contacts scale better than Silicide
  - Contact area and current crowding penalty for silicide

\[ \rho_c = 1 \times 10^{-9} \, \Omega \cdot \text{cm}^2 \]
ZnO as an IL

<table>
<thead>
<tr>
<th>IL</th>
<th>$E_g$ (eV)</th>
<th>$a$ (Å)</th>
<th>$\varepsilon$</th>
<th>$m^*$</th>
<th>$\Delta E_c$ (Ge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>8.8</td>
<td>4.785</td>
<td>9</td>
<td>0.2</td>
<td>2.8</td>
</tr>
<tr>
<td>GeO$_2$</td>
<td>4.3</td>
<td>4.402</td>
<td>5.9</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>5.3</td>
<td>7.608</td>
<td>7</td>
<td>0.2</td>
<td>1.9</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>3.05</td>
<td>4.593</td>
<td>80</td>
<td>0.3</td>
<td>-0.06</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.37</td>
<td>3.249</td>
<td>9</td>
<td>0.3</td>
<td>-0.1</td>
</tr>
</tbody>
</table>
Interlayer (IL) Comparison

- ZnO gives lowest $\rho_c$ for thick films

FERMI LEVEL PINNING
ELECTROSTATICS

\[
D_{\text{MIGS}} = \frac{2}{\pi a^2 E_g}
\]

\[
\delta_{\text{IL}} = \frac{h^2}{2\pi m_0 a E_g}
\]

\[
D_{\text{MIGS}(t)} = D_{\text{MIGS}} e^{-\frac{t}{\delta_{\text{IL}}}}
\]

\[
S = \left(1 + \frac{q^2 D_{\text{MIGS}(t)}(\varepsilon_{\text{Ge}} + \varepsilon_{\text{IL}})}{\varepsilon_0 (\varepsilon_{\text{IL}} + \varepsilon_{\text{Ge}})}\right)^{-1}
\]

\[
\Phi_{\text{Meff}} = S \Phi_M + (1 - S) \Phi_{\text{CNLS}}
\]

- S. Gupta et al., Journal of Applied Physics (2013)
Effect of Doping ZnO

- $\rho_c$ decreases with increasing doping
- At high doping, $\rho_c$ independent of thickness

S. Gupta et al., Journal of Applied Physics (2013)
Device Fabrication

- N-Ge Substrate Pre-Clean
- Lithography on n⁺ epi-Ge
- PVD ZnO, Ti/Au Diode formation
- Back Al metallization
- PDA in N₂ forming high doped ZnO
- Liftoff
- PDA in N₂
- Forming high doped ZnO
- Ti/Au
- C-TLM

TEM of n-Ge/ZnO/Ti interface

Tauc plot of the deposited ZnO film. Measured $E_g$ ~3.1eV
J-V Characteristics

- As expected significant increase in on and off currents for n-Ge
- NiGe/n-Ge and Ti/n-Ge control devices are pinned near VB
- ALD ZnO also shows a similar response as PVD ZnO
• ZnO shows reduction in $\rho_c$ for Ge (2.5x) and Si:C (1.3x)
• Benefit reduces with increasing substrate doping
  \[ \Delta \rho_{\text{Si}} < \Delta \rho_{\text{Si:C}} < \Delta \rho_{\text{Ge}}, \quad N_{\text{Si}} > N_{\text{Si:C}} > N_{\text{Ge}} \]
Summary: Contact resistance vs Ge doping

• ZnO helps lower doping requirement for contacts to n-Ge
  – 1e20 cm⁻³ S/D doping with ZnO IL should reach ITRS spec (2014)

• P. Parahamans et al., p. 83-84, VLSI Symposium 2012
MoS$_2$: Key Features

- Graphene
  - Unique properties of Graphene have led to interest in 2D materials
  - Linear dispersion relationship $\mu = 10^6$ cm$^2$/V.s at 2K
  - Semi-metallic (zero bandgap) nature makes it unsuitable for logic applications

- MoS$_2$
  - Layered with strong in-plane bonding and weak out-of-plane interactions
  - Enables exfoliation of monolayer
  - Large intrinsic band gap e.g. 1.8 eV in monolayer and 1.29 eV in multilayer
  - Monolayer $\rightarrow$ Direct band gap
  - Good for optoelectronic application
  - Thermal stability up to 1100°C


25/02/2016
Group 4-7 TMDs are layered, whereas group 8-10 TMDs are non-layered structures.

About 40 different layered TMD compounds exist.
How good can a monolayer MoS$_2$ transistor be?

➢ $I_{ON}/I_{OFF} \rightarrow >10^{10}$
➢ $DIBL \sim 10$ mV/V, SS $\rightarrow$ 60 mV/decade
➢ $L_g = 15$ nm
➢ $\text{HfO}_2$ $T_{ox}$ $2.5$ nm

Device Fabrication

➢ Transistor process flow

➢ TLM structure process flow to estimate contact resistance ($R_c$)

➢ SEM image of monolayer MoS$_2$ device

- P$^+$ Si as Back gate
- 280 nm SiO$_2$
- Reactive ion etching
- Surface treatment
- MoS$_2$ exfoliation
- PMMA Resist coating
- Source/Drain EBL Patterning
- Metallization
- Lift off

25/02/2016
Characterization of MoS$_2$ layers

- Optical micrograph showing Bilayer MoS$_2$
- AFM data for Bilayer MoS$_2$ flake
- Raman spectrum of Bilayer MoS$_2$ flake

Optical micrograph showing Bilayer MoS$_2$

- Raman shift (cm$^{-1}$)
- Intensity (a.u.)

$\Delta K = 21.6$ cm$^{-1}$

Raman shift (cm$^{-1}$)

Intensity (a.u.)

AFM data for Bilayer MoS$_2$ flake

XPS spectra of MoS$_2$ flake
High Contact Resistance

- Large contact resistance at metal-MoS$_2$ interface

![Graph showing contact resistance versus voltage](image)

\[ R_C \sim \frac{h}{2q^2M} \]

- Contact resistance limited by sheet charge density

\[ R_CW \sim \frac{0.026}{\sqrt{n_{2D}}} \Omega\text{.mm} \]


- Different approaches to reduce the contact resistance

N-type doping of MoS$_2$

<table>
<thead>
<tr>
<th>Ref. no.</th>
<th>Charge transfer</th>
<th>$\Phi$</th>
<th>$\Delta$</th>
<th>$\mu$ (cm)</th>
<th>Stability</th>
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<tbody>
<tr>
<td>[1]</td>
<td>Potassium</td>
<td>NA</td>
<td>NA</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>[2]</td>
<td>PEI</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>No</td>
</tr>
<tr>
<td>This work</td>
<td>TiO metal</td>
<td>40 meV, constant $\Phi$</td>
<td>13X↓</td>
<td>Up to 11X↑</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\[ \Phi_B \text{ thinner} \]
\[ \Phi_B \text{ lower} \]

Fermi-level unpinning

Ref. no. 25/02/2016

TiO$_2$ as an interfacial layer

- Why is TiO$_2$ a good interfacial layer candidate?
  - Small or no conduction band offset → low tunneling R
  - Large bandgap → Fermi-level unpinning
  - Ultra-thin IL → low tunneling R

- Energy band alignment of MoS$_2$ and TiO$_2$ suggests possibility of charge transfer from TiO$_2$ to MoS$_2$

Device fabrication: Process flow

- Transistor process flow

- Optical micrograph of back gated transistor

- Scanning electron microscope image showing devices with different channel length

- P⁺ Si as Back gate
- 280 nm SiO₂
- Reactive ion etching
- Surface treatment
- MoS₂ exfoliation
- Source/Drain EBL Patterning
- ALD TiO₂
- Metallization and Lift Off

Date: 25/02/2016
Contact resistance using TLM

- Reduction in contact ($R_c$) and transfer length ($L_T$)

- Resistor network model for metal-semiconductor contacts

Reduction in $L_T$ for contact-
Barrier height extraction

- Reduction in effective SBH with TiO$_2$ IL for Au, Pd, Ni and Ti

- Constant effective SBH with TiO$_2$ IL indicates increase in doping instead of $\phi_B$ reduction

25/02/2016
Electrical characteristics

- **SEM images of TLM devices with and without TiO$_2$**

- **Metal-MoS$_2$** → High resistance, large SBH
- **Metal-TiO$_2$-MoS$_2$** → Low resistance, small SBH
- **Metal-TiO$_2$-MoS$_2$ -Metal** → Asymmetric I-V confirms significant difference in barrier heights
Transistor Characteristics

- Improvement in on-current and field effect mobility with TiO$_2$ IL for different metals
- Larger change with Pd
Physical proof of charge transfer

- XPS spectra shows Mo-3d, and S-2p core level shifts to higher binding energy from MoS$_2$ to TiO$_2$-MoS$_2$

- UPS measurements of TiO$_2$-MoS$_2$ and MoS$_2$

- Reduction in work-function (0.3 eV) with Ti
- Larger benefit from reduction in contact resistance vs mobility enhancement from dielectric screening
Conclusion

- N-type doping by charge transfer mechanism

- Improvement in $I_{ON}/I_{OFF}$ with TiO$_2$ and constant $\Phi_B$ irrespective of metal work function

Summary

• Metal-semiconductor contacts are a part of every semiconductor device
  – Low contact resistance is critical for high performance

• Diodes ($\varphi_B$) and TLM ($\rho_c$) structures are used for extracting contact parameters

• Fermi-level pinning, low doping activation are leading causes of high resistance

• Emerging materials need novel solutions to reduce contact resistance
Thank you!
Backup
Measurement of $R_C$ and $\rho_C$

$$R_f = \frac{\left(\frac{V_{56}}{I_{23}}\right) l_1 - \left(\frac{V_{45}}{I_{12}}\right) l_2}{2(l_1 - l_2)}$$

$$= \frac{\sqrt{R_s} \rho_c}{w \tanh (\sqrt{R_s}/\rho_c l)}$$