Deviations from simple theory and metal-semiconductor junctions

- 5.6 Deviation from the simple theory
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Effects of contact potential on carrier injection

- The contact potential limits the ultimate voltage that will appear across the junction.
  - Assumed **high level injection** (take into account changes majority carrier concentration)

$$\frac{\mathrm{p_p} + \Delta \mathrm{p_p}}{\mathrm{p_n} + \Delta \mathrm{p_n}} = \frac{\mathrm{n_n} + \Delta \mathrm{n_n}}{\mathrm{n_p} + \Delta \mathrm{n_p}} = e^{q(V_o - V)/kT}$$

- Simple theory will not predict this ($e^{qV/kT}$)
  - Assumed **low level injection** (neglect changes majority carrier concentration)

Effects of contact potential on carrier injection

For a p^+/n Si diode :

E_g, m_e^*, and m_h^*

are rolled up into $n_i = 1.5 \times 10^{10}\,\mathrm{cm}^{-3}$

(At 300K)

$N_a = 4 \times 10^{18}\,cm^{-3}$

$N_d = 1 \times 10^{16}\,cm^{-3}$

$\tau_p = \tau_n = 1 \times 10^{-6}\,s$

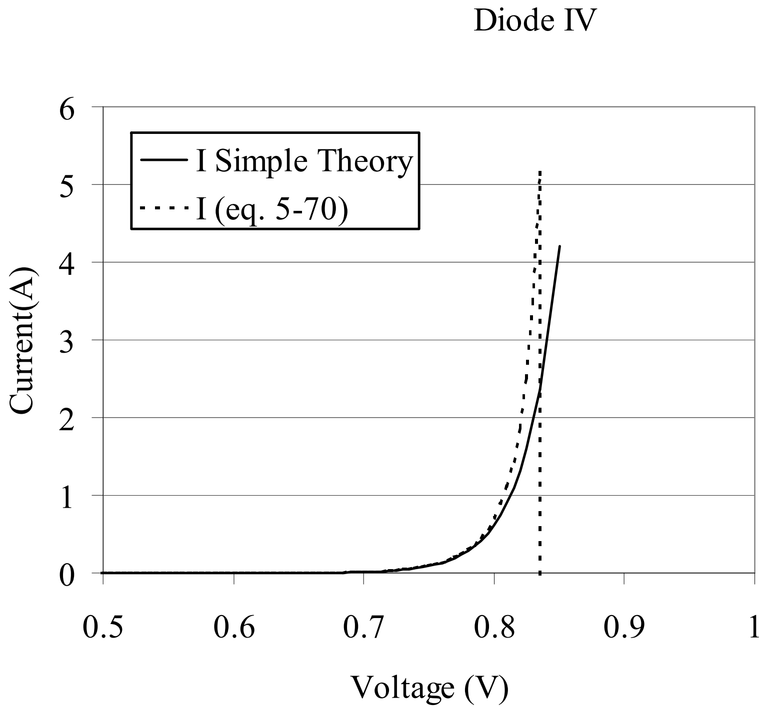
$\mu_n = 300 cm^2/V - s$ (e^- in p-region)

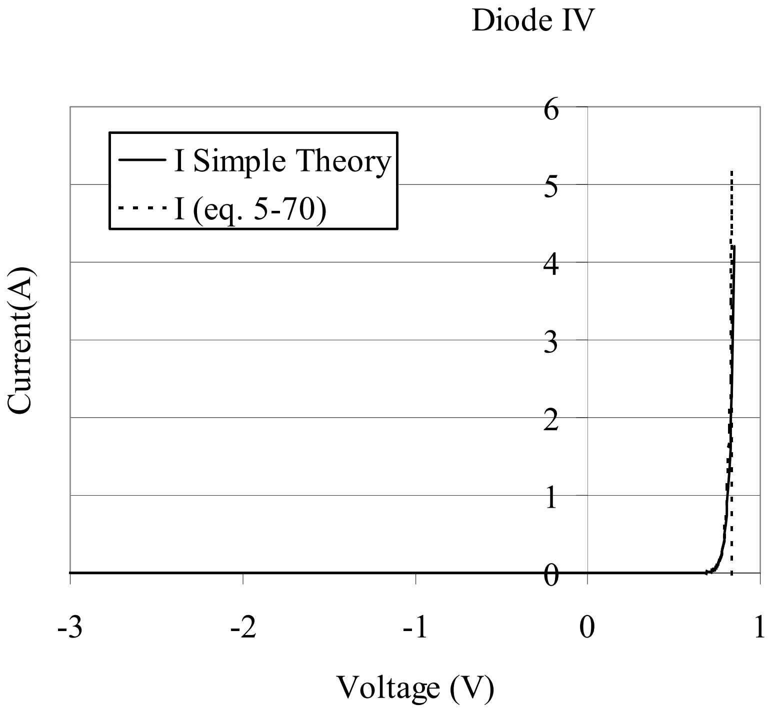
$\mu_p = 400 cm^2/V - s$(h^+ in n-region)

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV/kT} - 1\right)$$

$$I = qA\left[\frac{e^{qV/kT} - 1}{1 - e^{-2q(V_o - V)/kT}}\right]\left[\frac{D_p p_n}{L_p}\left(1 + \frac{n_i^2}{p_p^2}e^{qV/kT}\right) + \frac{D_n n_p}{L_n}\left(1 + \frac{n_i^2}{n_n^2}e^{qV/kT}\right)\right]$$

Effects of contact potential on carrier injection





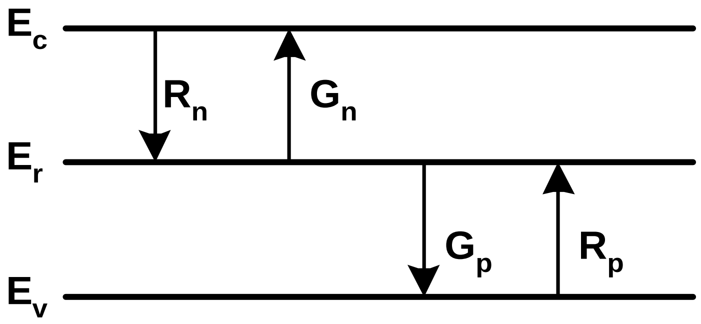
Recombination and generation in the transition region

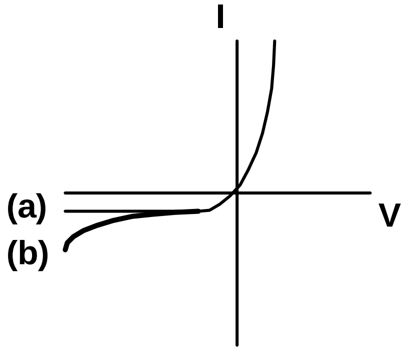
- Significant recombination and thermal generation of EHPs can occur if the depletion width is similar in length to L_n and L_p.
  - Forward bias: Recombination within W can lower current and is proportional to n_i and forward bias ($e^{qV/\mathbf{2}kT}$). Recombination within the neutral regions is proportional to $n_i^2/N_{(d\ \mathrm{or}\ a)}$ and forward bias ($e^{qV/\mathbf{1}kT}$).
  - This gives rise to the ideality factor, n.

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV/nkT} - 1\right)$$

Recombination and generation in the transition region

- Significant recombination and thermal generation of EHPs can occur if the depletion width is similar in length to L_n and L_p.
  - Reverse bias: Carrier generation can increase reverse saturation current, and even become voltage dependant with a trap near mid-gap.





Ideality Factor

$$G = \left[\frac{\sigma_p \cdot \sigma_n \cdot \upsilon_{th} \cdot N_t}{\sigma_n \cdot e^{\frac{(E_t - E_i)}{k \cdot T}} + \sigma_p \cdot e^{\frac{(E_i - E_t)}{k \cdot T}}} \right] \cdot n_i$$

$$J_F = A \cdot e^{\frac{q \cdot V}{\eta \cdot k \cdot T}}$$

$$G = \frac{n_i}{\tau_g}$$

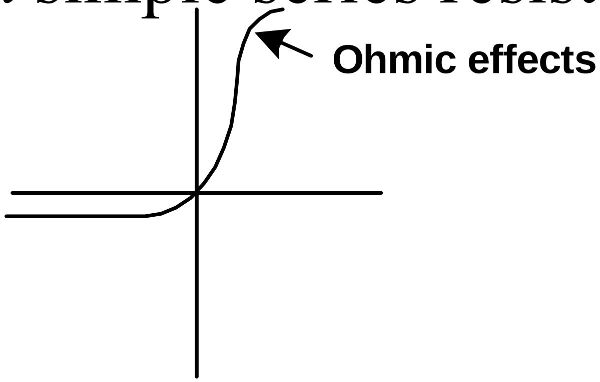
$$J_R = q \cdot \sqrt{\frac{D_p}{\tau_p}} \cdot \frac{n_i^2}{N_D} + \frac{q \cdot n_i \cdot W}{\tau_g}$$

Na much larger than Nd

$$J_F = q \cdot \sqrt{\frac{D_p}{\tau_p}} \cdot \frac{n_i^2}{N_D} \cdot e^{\frac{q \cdot V}{k \cdot T}} + \frac{q \cdot n_i \cdot W}{\tau_g} \cdot e^{\frac{q \cdot V}{2k \cdot T}}$$

Ohmic losses

- Ohmic losses will become significant when:
  - One of the neutral is very lightly doped
  - The area is close to the length of the neutral regions.
  - Operating at very high currents
- Ohmic losses will reduce current because less voltage is falling across the junction
- The resistance is dependant on the current, thus we can not add a simple series resistance.

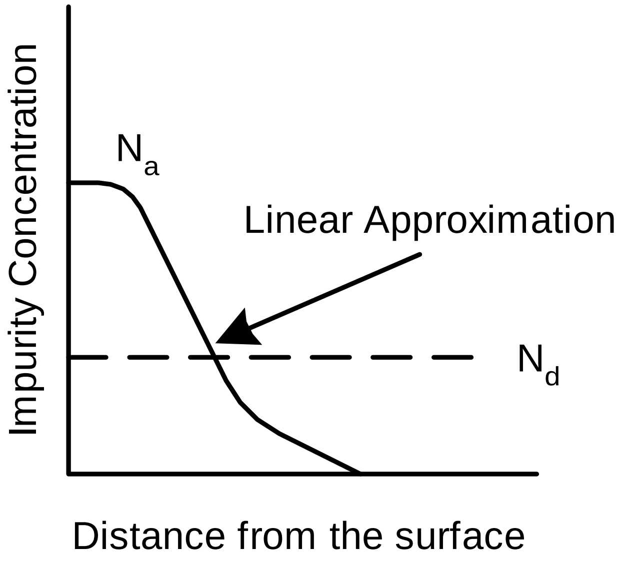


Graded junctions

- Not all junctions are abrupt
  - Drive-in diffusions are linearly graded around the junction. (Pre-dep diffusions are considered abrupt.)

$$N_d - N_a = Gx$$

$$\frac{dE}{dx} = \frac{q}{\varepsilon}\left(p - n + N_d^{\ +} - N_a^{\ -}\right) \approx Gx$$



Graded junctions

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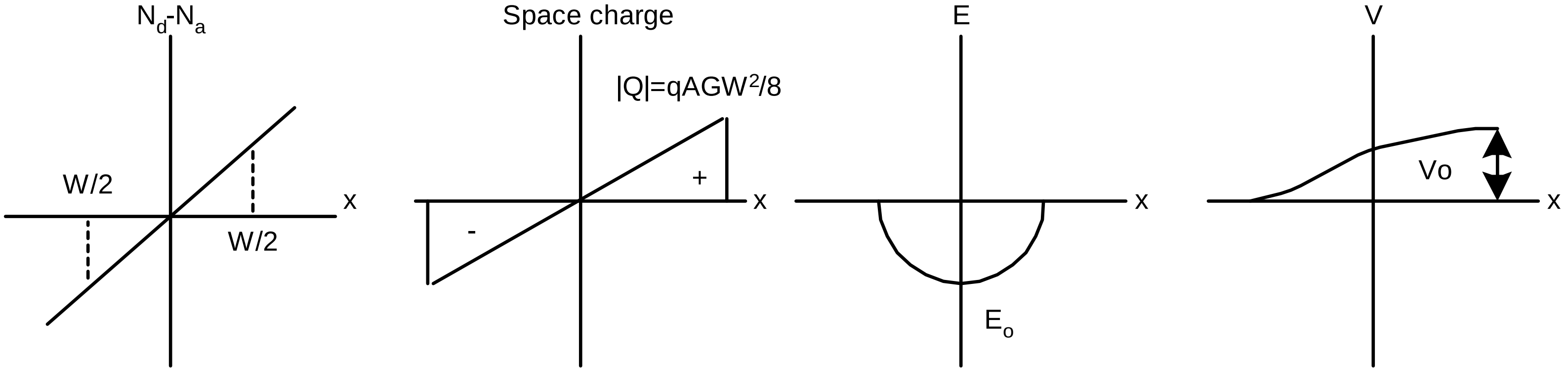
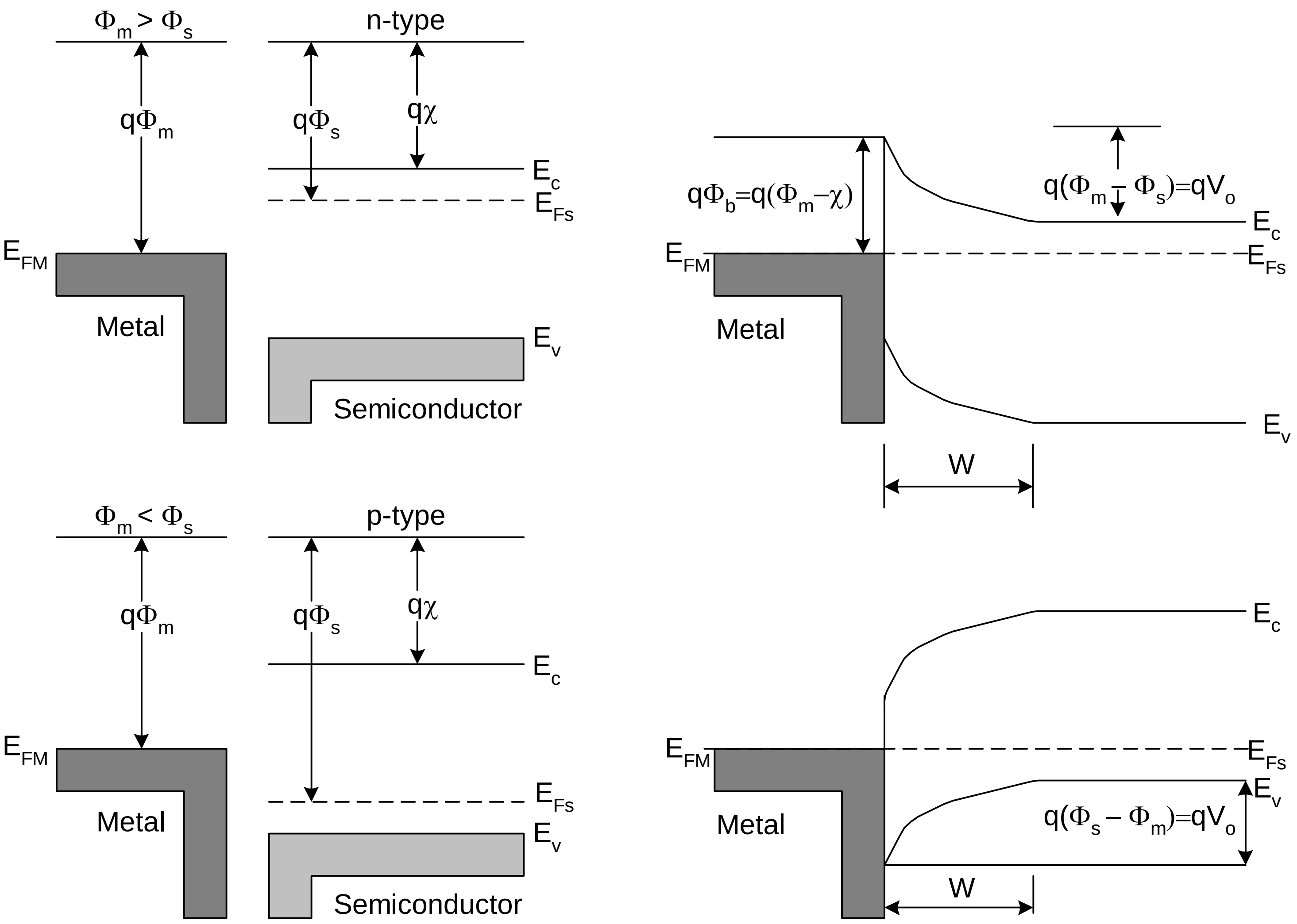


- Boundaries between space charge and neutral regions are blurred. No analytic solutions available.

Schottky barriers

- Diode like behavior can be mimicked by applying clean metal to a clean semiconductor.
  - Easy to do and faster switching times can be realized.
- n-type
  - Semiconductor bands bend up causing a more positive region near the interface, which attracts electrons from the metal to the interface interface.
- p-type
  - Semiconductor bands bend down causing a more negative region near the interface, which attracts holes from the metal to the interface.

Schottky barriers



Rectifying contacts

- Apply a forward bias to the Metal of the M/S(n) diode and the contact potential is reduced by V_o-V
  - Allows electrons to diffuse into metal.
- Apply a forward bias to the Semiconductor of the M/S(p) diode and the contact potential is reduced by V_o-V
  - Allows holes to diffuse into metal.

Rectifying contacts

- Apply a reverse bias to the Metal of the M/S(n) diode and the contact potential is increased by V_o+V_r.
  - Electrons have to overcome a voltage independent barrier to diffuse into metal.
- Apply a reverse bias to the Semiconductor of the M/S(p) diode and the contact potential is reduced by V_o+V_r.
  - Holes have to overcome a voltage independent barrier to diffuse into metal.

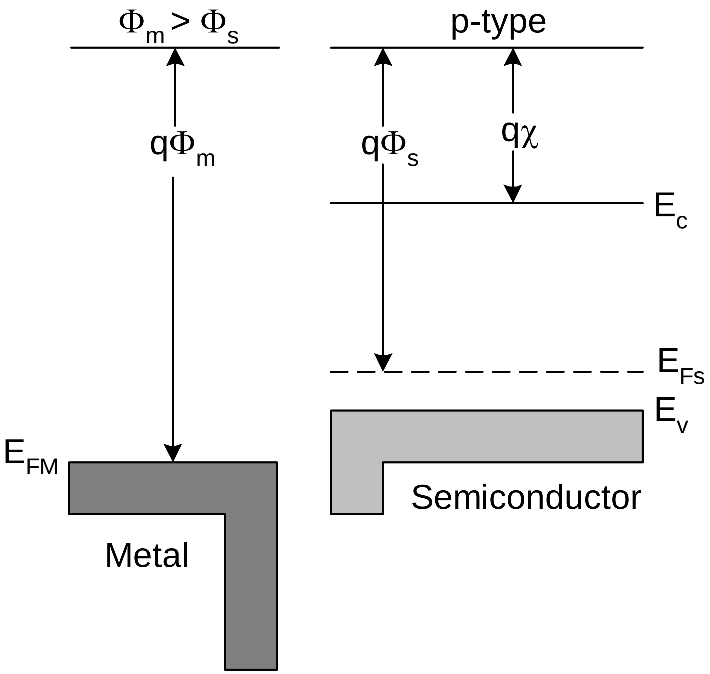
Rectifying contacts

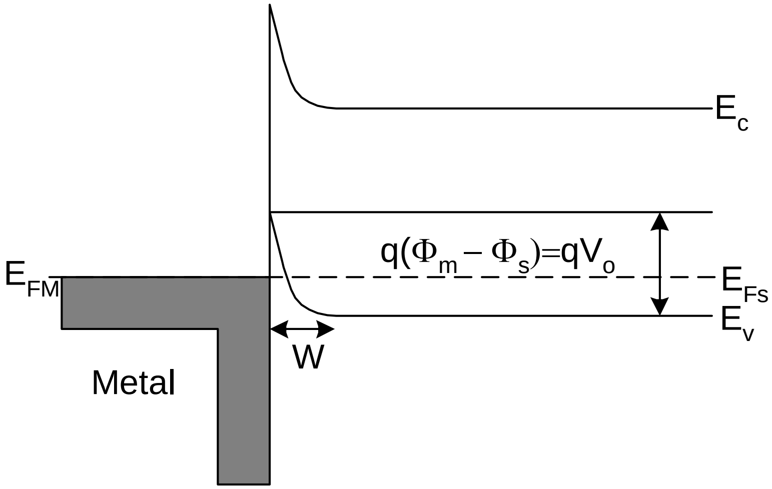
- Current flows primarily by **majority** carriers is both cases.
- Very little charge storage occurs, which leads to **fast switching speeds**.

Ohmic contacts

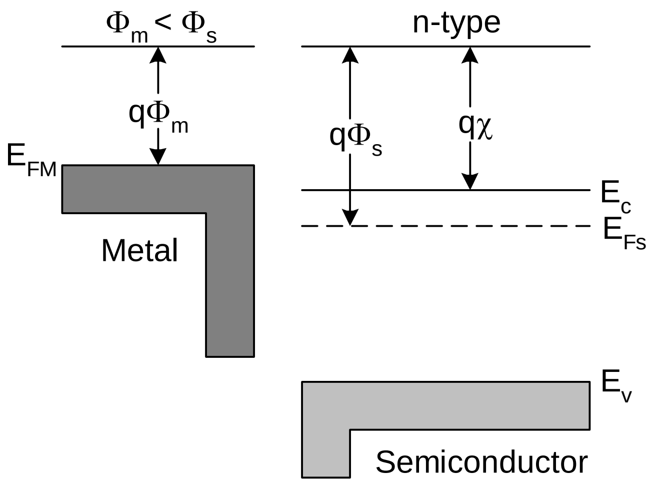
- Metal/semiconductor ohmic contacts
  - linear near the origin, non-rectifying
- Two methods of fabrication
  - Choose a metal with a workfunction that aligns the fermi levels with majority carriers. (Al for p-type Si, Au for n-type Si
  - Dope the semiconductor heavily so that W is very thin so that tunneling occurs (Al on p^+ or n^+ Si)
  - Heavy doping all ways improves ohmic behavior.

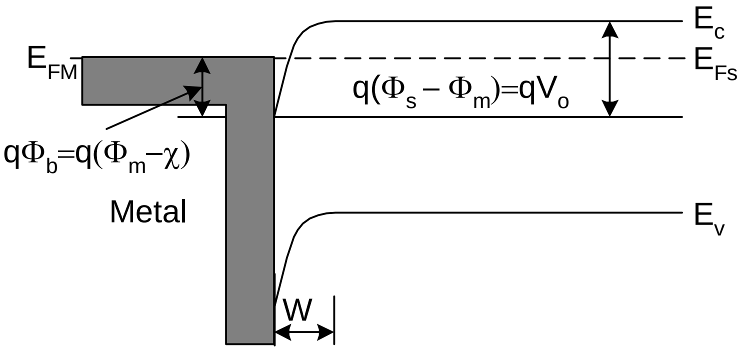
Ohmic contacts





Ohmic contacts





Real Schottky barriers

- In Si, there is a thin oxide in between the metal and semiconductor.
- Surface states arise from the crystal ending
  - This can pin the fermi level to midgap in GaAs
- If a metal semiconductor junction is alloyed the interface is blurred between metal/metal-semiconductor/semiconductor.
- Contact design is very dependant on your process.