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# Metal Semiconductor Contacts

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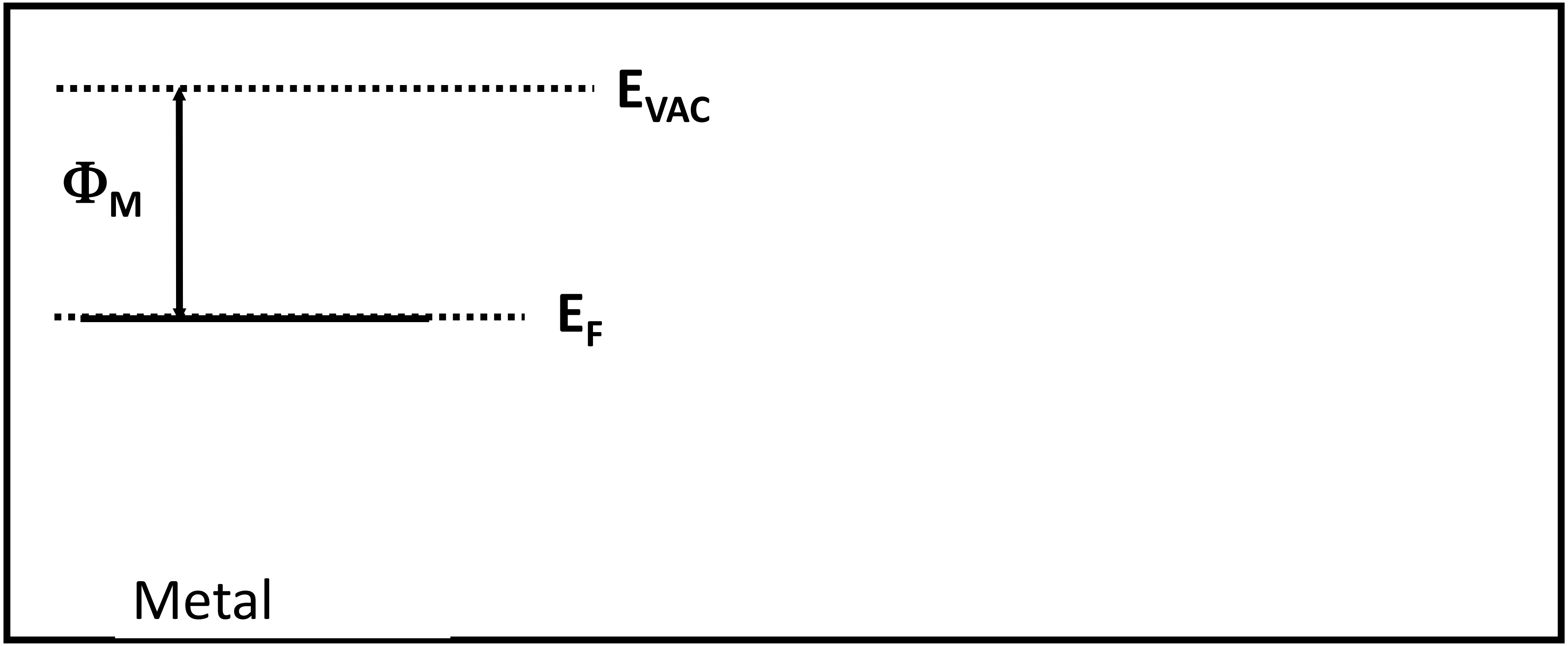
# Metal Semiconductor Contacts

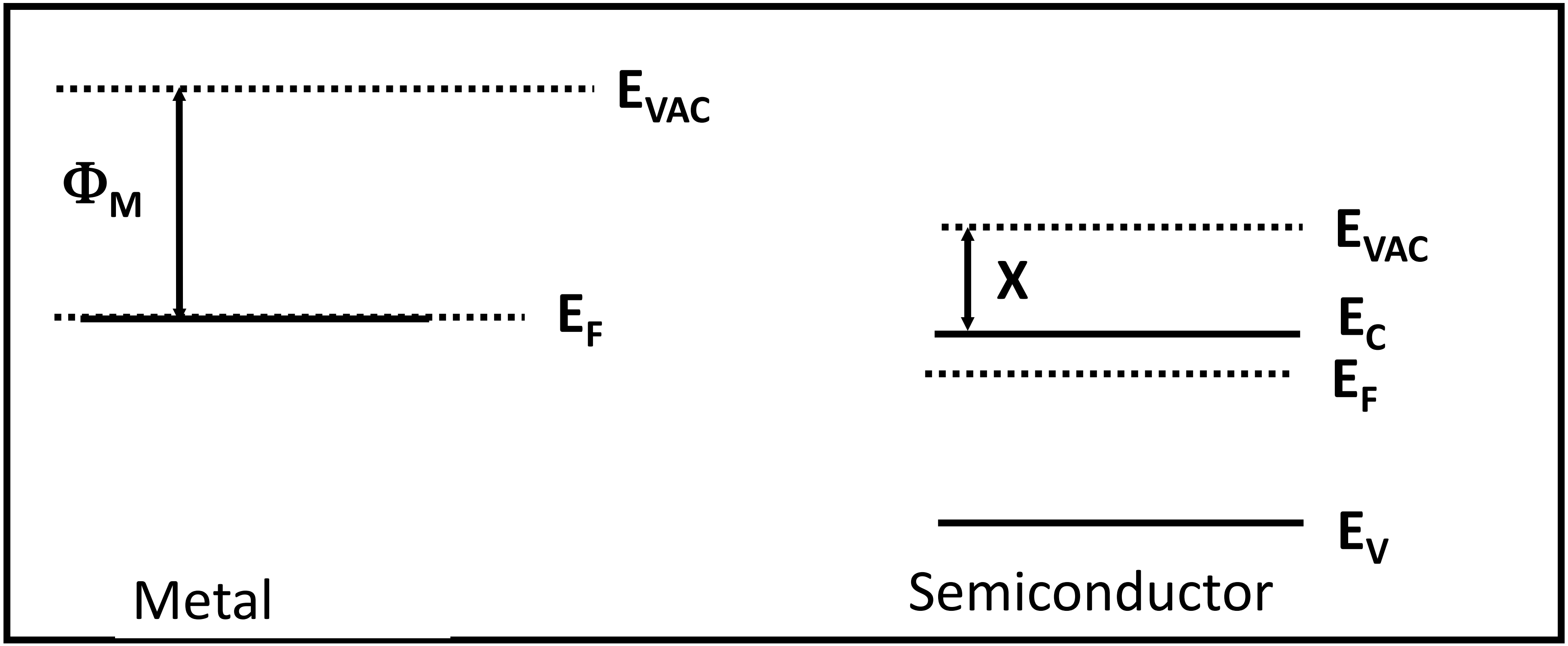
- Majority carrier device
  - High speed
- Rectifying contacts
  - High barriers
  - Moderate doping < $10^{17}$ $cm^{-3}$
- Ohmic contacts
  - Low barriers or
  - High doping

# Barrier Formation

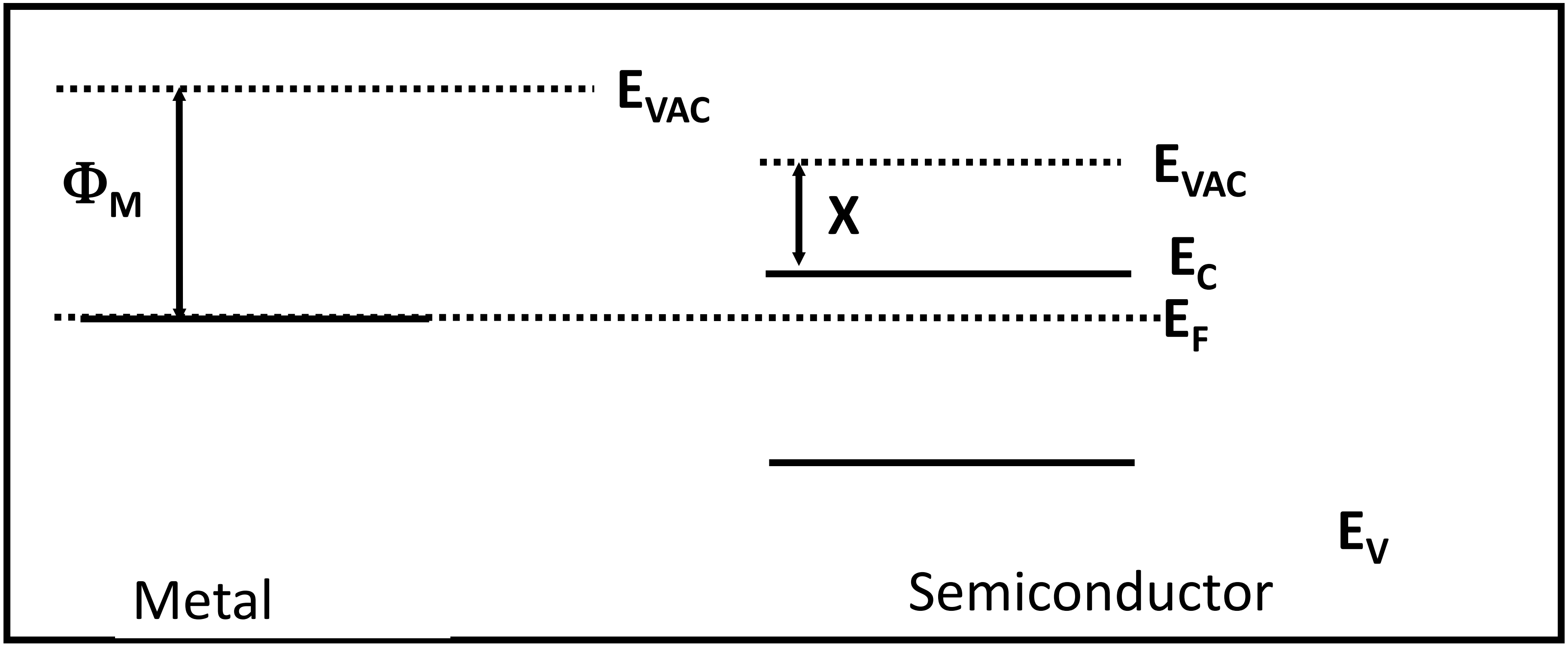
# Barrier formation



# Barrier formation



# Barrier formation



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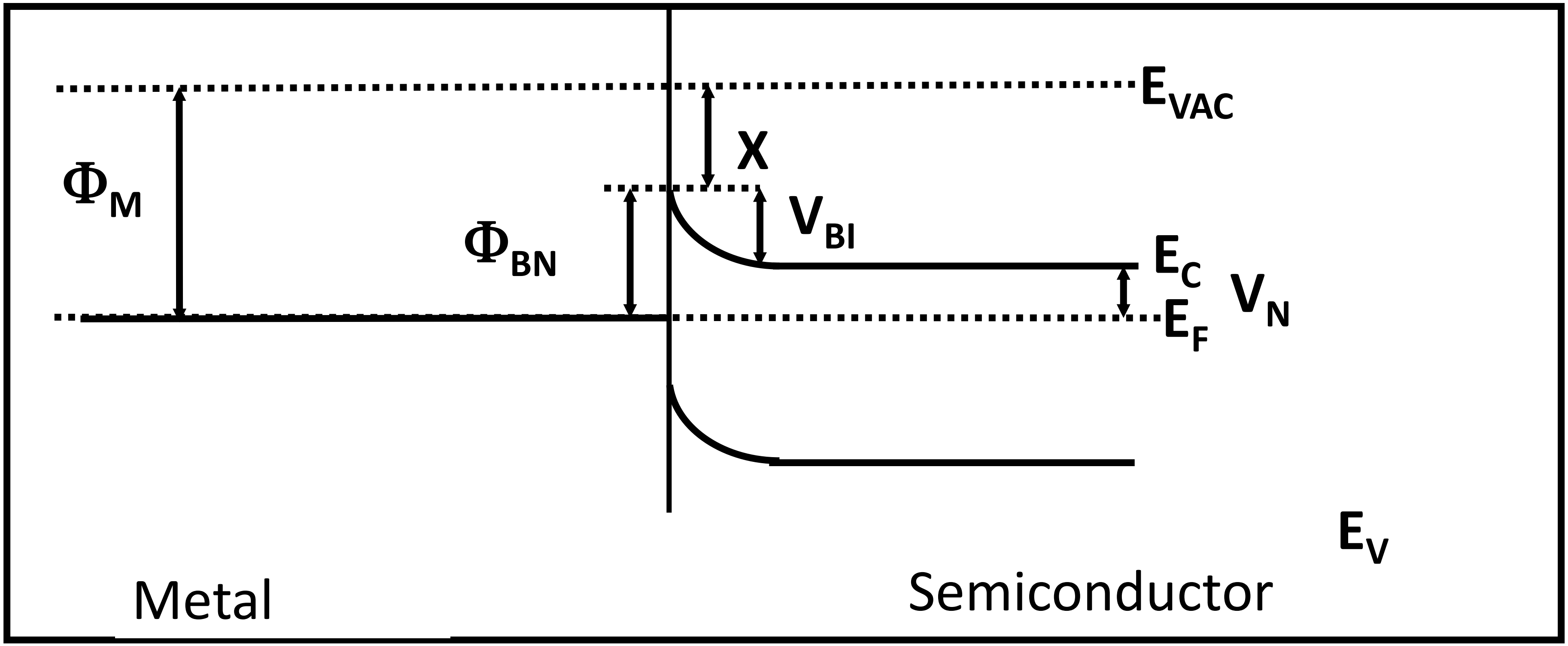
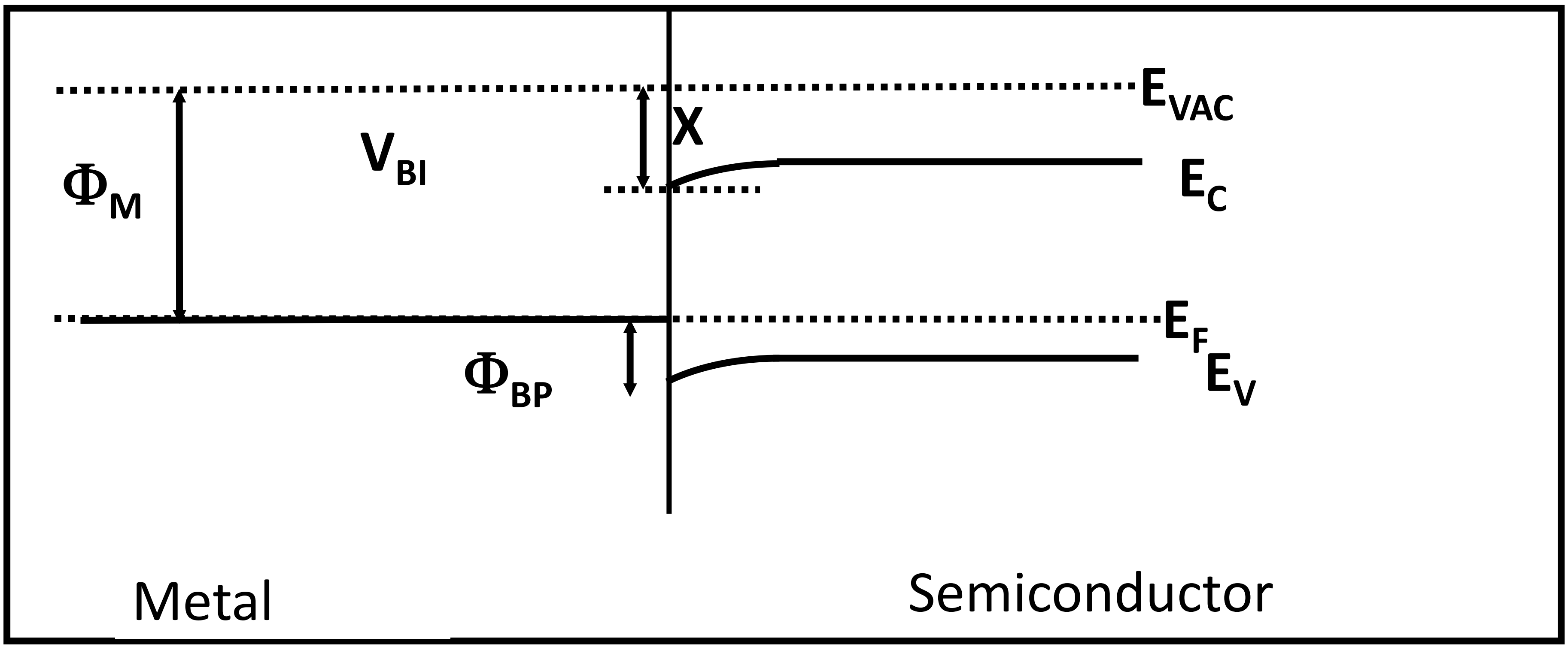


# Barrier formation

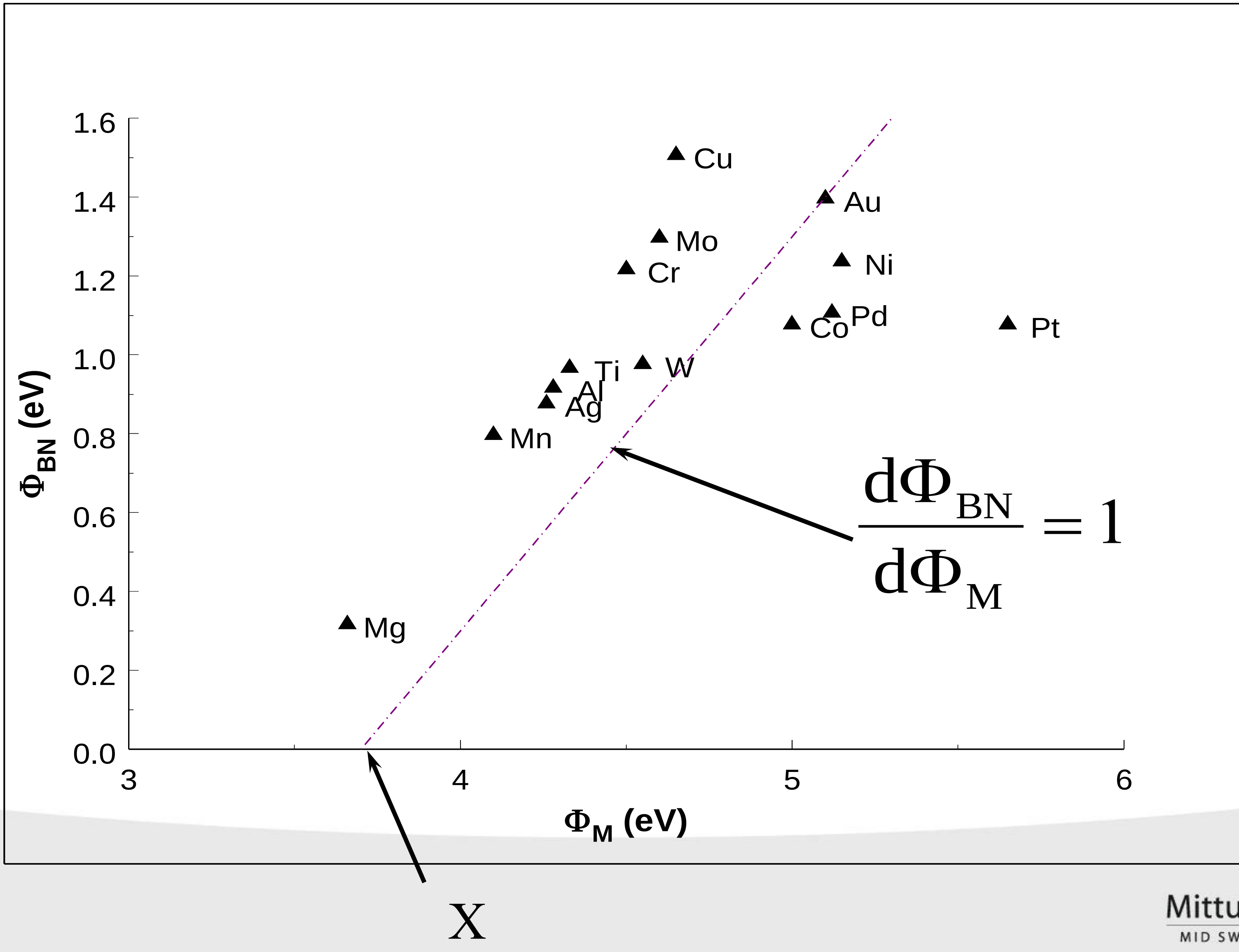


# Shottky-Mott barrier

- $\Phi_{BN} = \Phi_{M} - X$
- $\Phi_{BP} = X - \Phi_{M} + E_{G}$
- $\Phi_{BN} + \Phi_{BP} = E_{G}$

$$\frac{d\Phi_{BN}}{d\Phi_{M}} = 1$$

# Schottky barrier height vs. metal work function
# Schottky-Mott model




$$\frac{d\Phi_{BN}}{d\Phi_M} = 1$$

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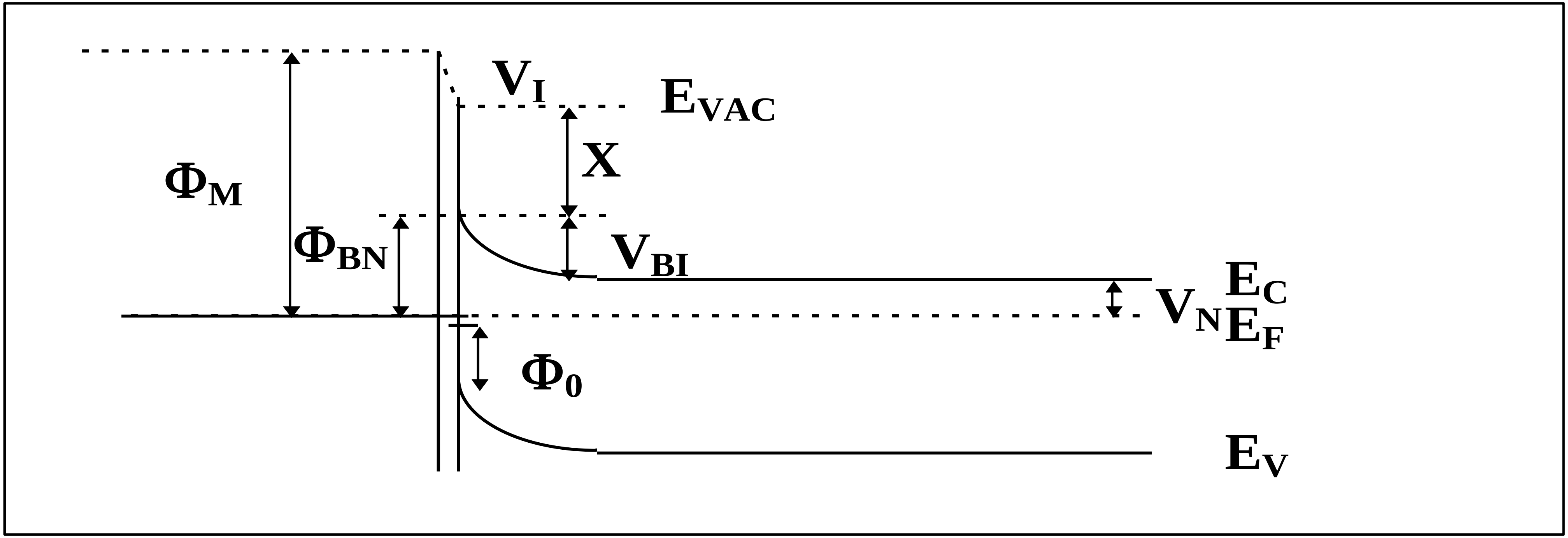
# Schottky Barrier formation
## Bardeen model




Metal Semiconductor

- The barrier height is determined by $\Phi_0$

$$\frac{d\Phi_{BN}}{d\Phi_{M}} < 1$$

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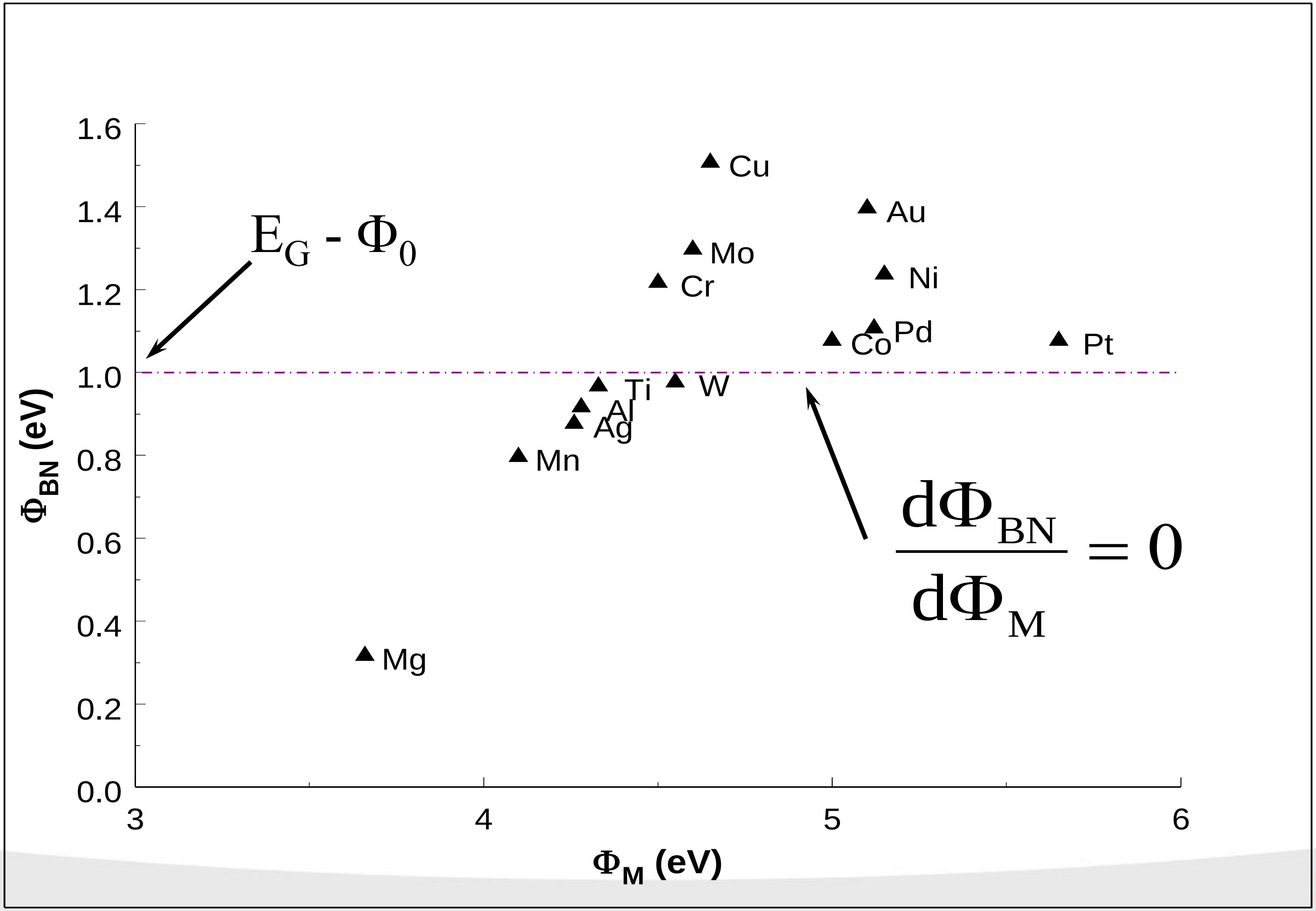
# Schottky barrier height vs. metal work function
# Bardeen model

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# General case

- $\Phi_{BN} = c_2 * \Phi_M + c_3$
  - $C_2 = 1$ -> Schottky
  - $C_2 = 0$ -> Bardeen

**Table 1** Summary of Barrier Height Data and Calculations of Interface Properties for Si, GaAs, GaP, and CdS (After Ref. 14)

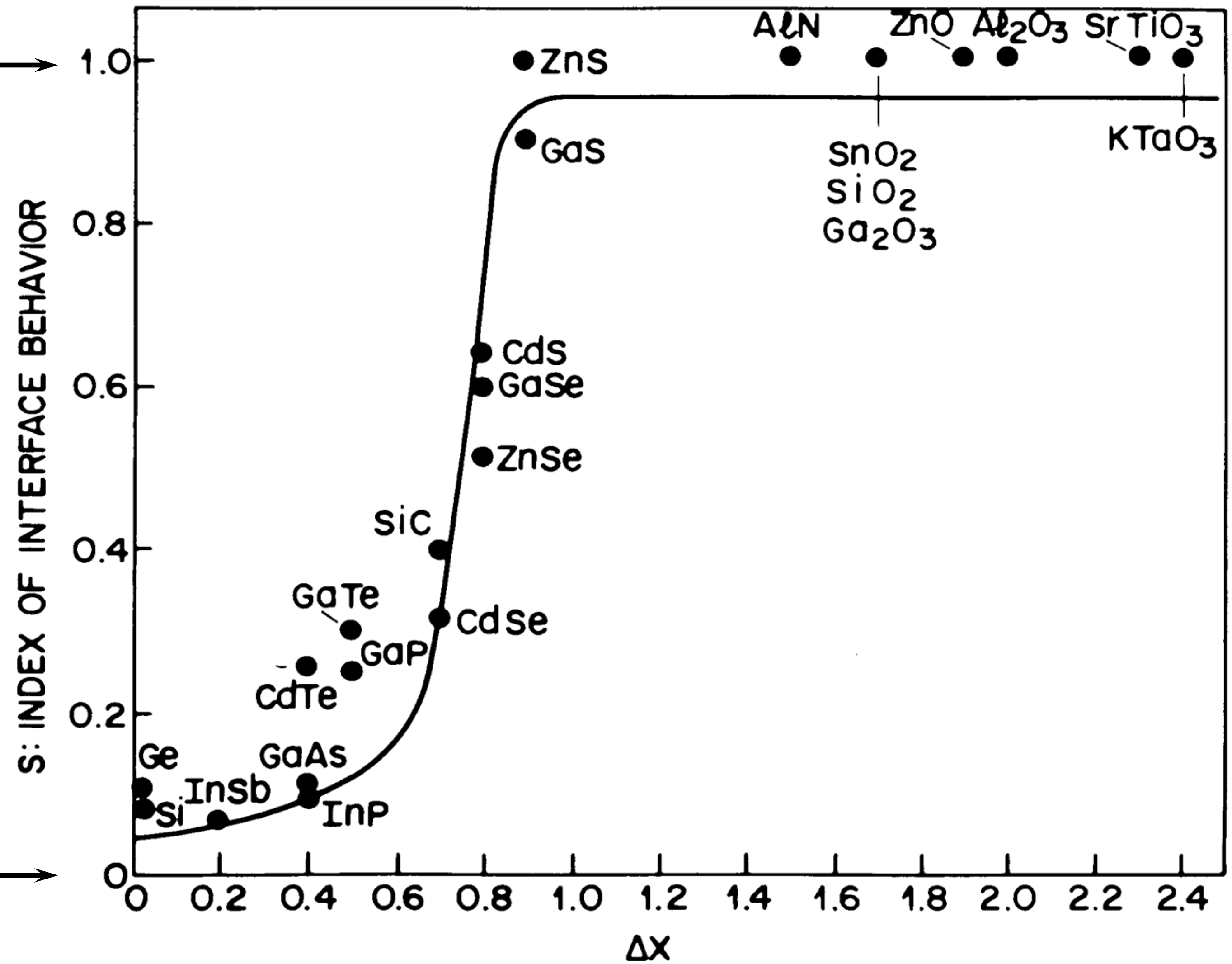
| Semi-conductor | $c_2$ | $c_3$ (V) | $\chi$ (V) | $D_{it}$ ($10^{13}$ /eV-cm$^2$) | $q\phi_0$ (eV) | $q\phi_0/E_g$ |
|---|---|---|---|---|---|---|
| Si | 0.27±0.05 | –0.52±0.22 | 4.05 | 2.7±0.7 | 0.30±0.36 | 0.27 |
| GaAs | 0.07±0.05 | 0.51±0.24 | 4.07 | 12.5±10.0 | 0.53±0.33 | 0.38 |
| GaP | 0.27±0.03 | 0.02±0.13 | 4.0 | 2.7±0.4 | 0.66±0.2 | 0.294 |
| CdS | 0.38±0.16 | –1.17±0.77 | 4.8 | 1.6±1.1 | 1.5±1.5 | 0.6 |

# Schottky barrier formation on different semiconductors

Schottky-Mott

$$S = \frac{d\Phi_{BN}}{dX_M}$$

Bardeen




$$\Delta X = \left| X_{S1} - X_{S2} \right|$$

# Schottky barrier lowering

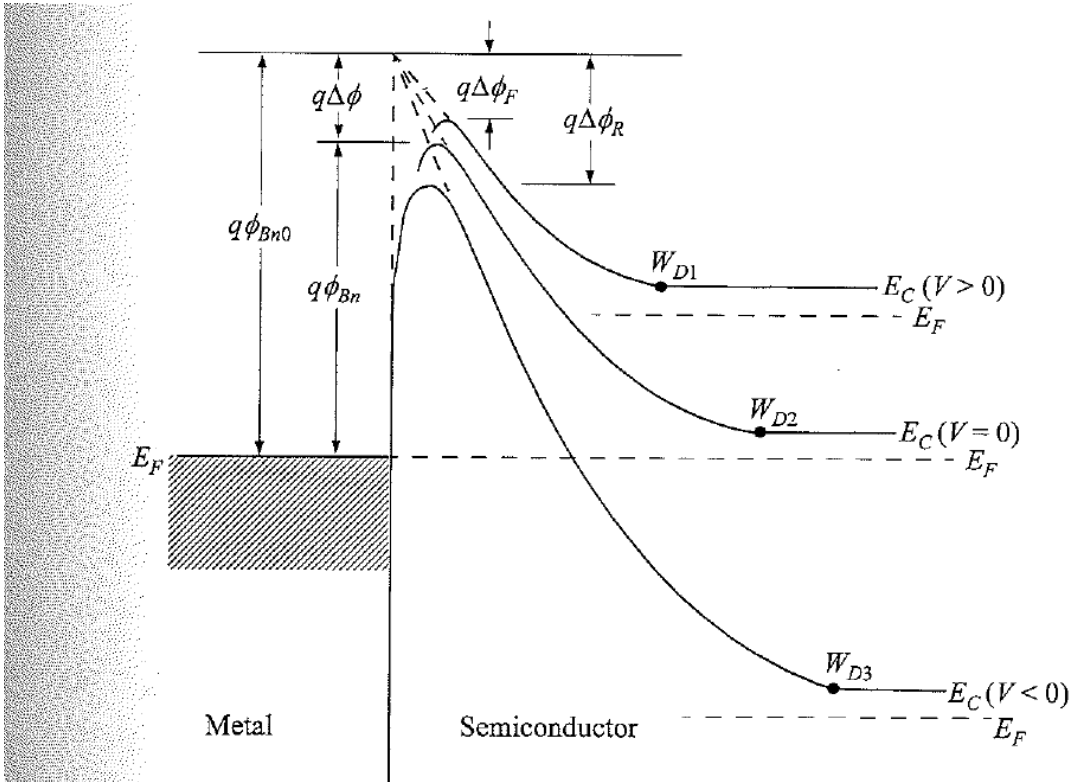



**Fig. 11** Energy-band diagram incorporating the Schottky effect for a metal *n*-type semiconductor contact under different biasing conditions. The intrinsic barrier height is $q\phi_{Bn0}$. The barrier height at thermal equilibrium is $q\phi_{Bn}$. The barrier lowerings under forward and reverse bias are $\Delta\phi_F$ and $\Delta\phi_R$ respectively. (After Ref. 10.)

# Charge transport

# Basic transport process

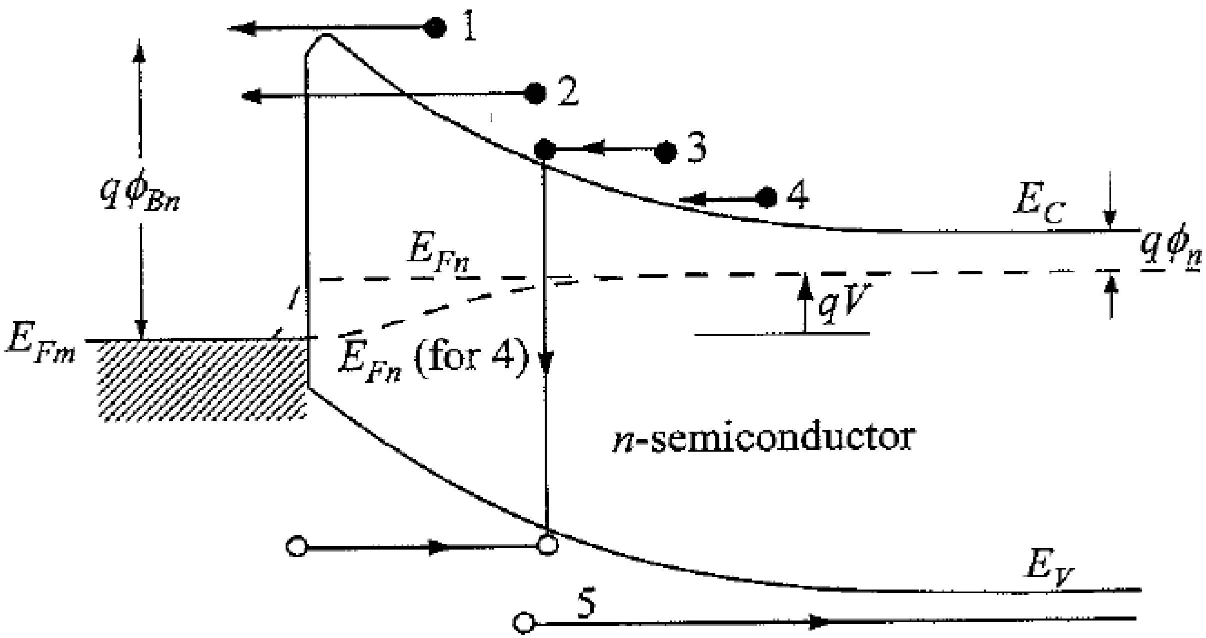



**Fig. 16** Five basic transport processes under forward bias. (1) Thermionic emission. (2) Tunneling. (3) Recombination. (4) Diffusion of electrons. (5) Diffusion of holes.

# Basic transport process

- Thermionic emission
  - The charge transport is limited by the emission over the barrier
    - High mobility
    - High barrier
    - ”unlimited” supply of carriers
- Diffusion
  - The charge transport is limited by diffusion of carriers into the depletion region
    - Low mobility
    - “Low” barrier
- Tunneling
  - Main charge transport is by tunneling through the barrier
    - High doping

# Current voltage characteristics

- Thermionic emission

$$I = SA^{*}T^{2}\exp\left(-\frac{q\Phi_B}{kT}\right)\left(\exp\left(\frac{qV}{nkT}\right)-1\right)$$

-Thermionic emission diffusion theory

  -A* replaced by A** taking effects of diffusion into account

# Current voltage characteristics

- General characteristics

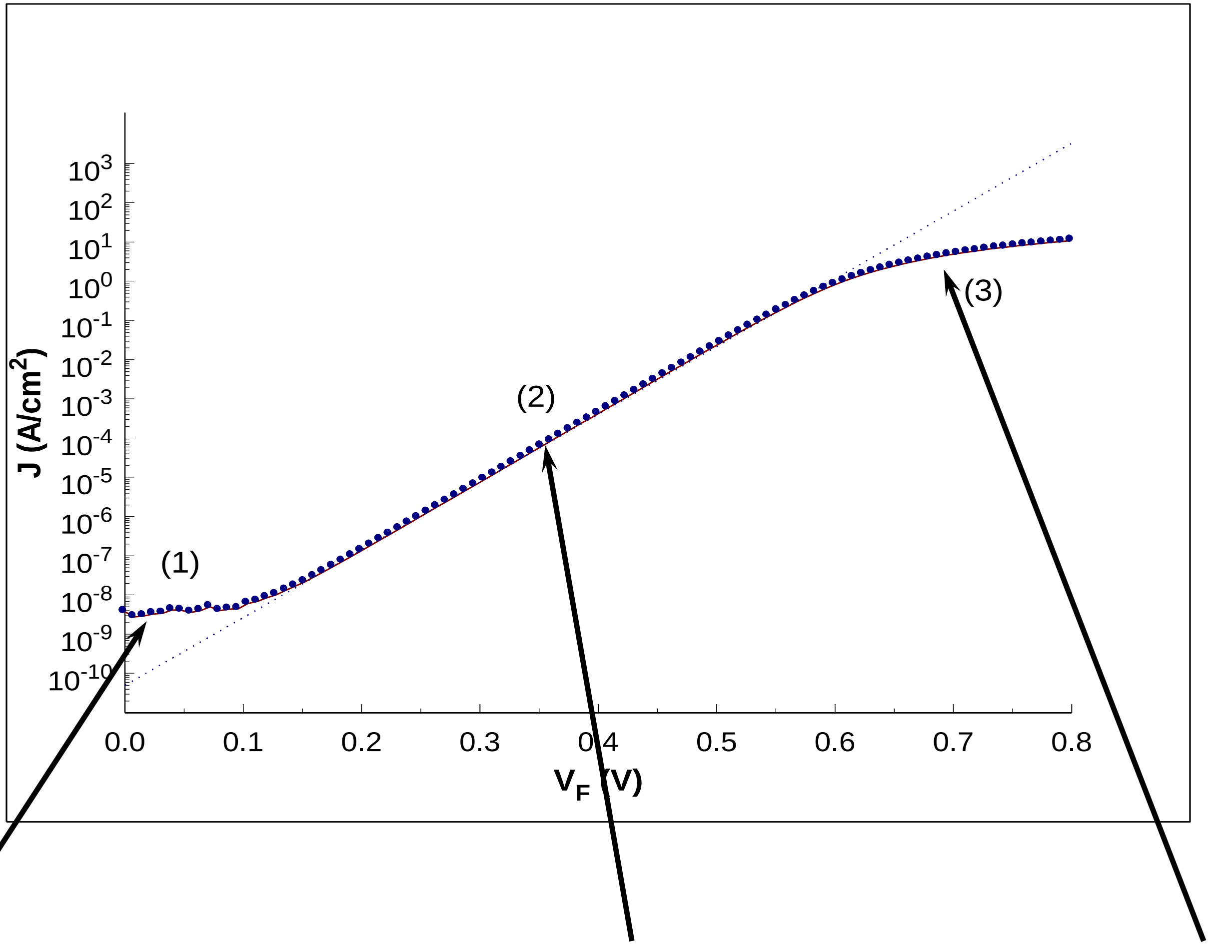
$$I = I_0 \left( \exp\left( \frac{qV}{nkT} \right) - 1 \right)$$

-Expression for $I_0$ depends on type of charge transport

-Typically a combination

- Forward direction
  - Barrier height and ideality factor calculated from a plot of ln(I) vs. V

# Current voltage characteristics




Below resolution Linear Series resistance

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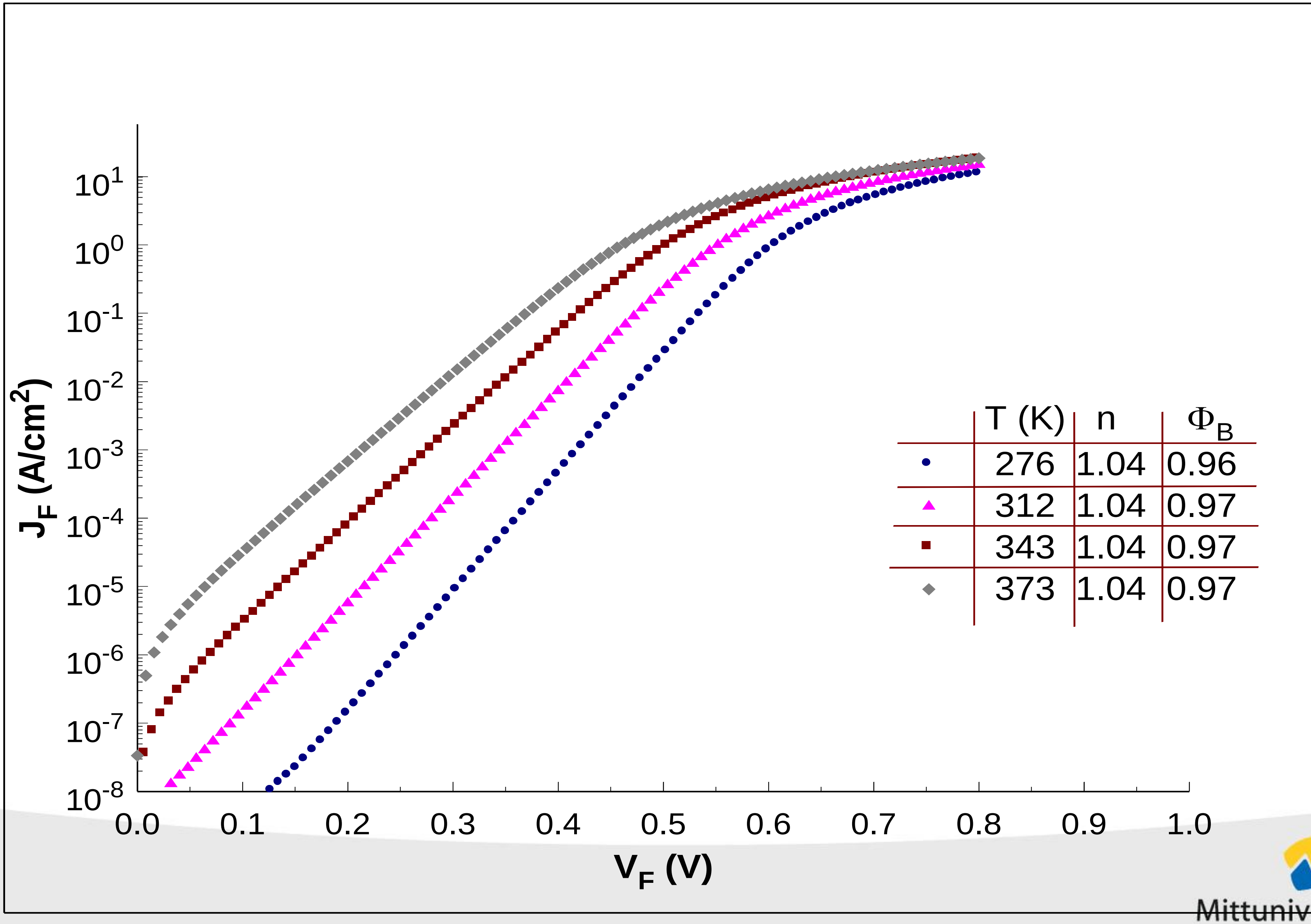
# Current-voltage characteristics for a Ti n-SiC Schottky diode

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# Current voltage characteristics

- Reverse direction
    - Current should saturate for thermionic emission

- Factors increasing the reverse current

    - Schottky barrier lowering

$$I_r \propto \exp\left(V^{1/4}\right)$$

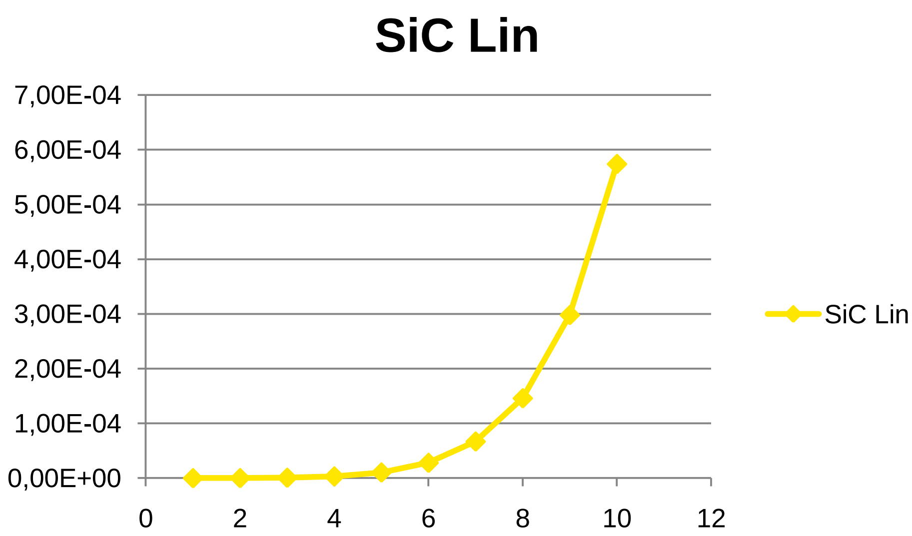
    - Interfacial layers in the barrier

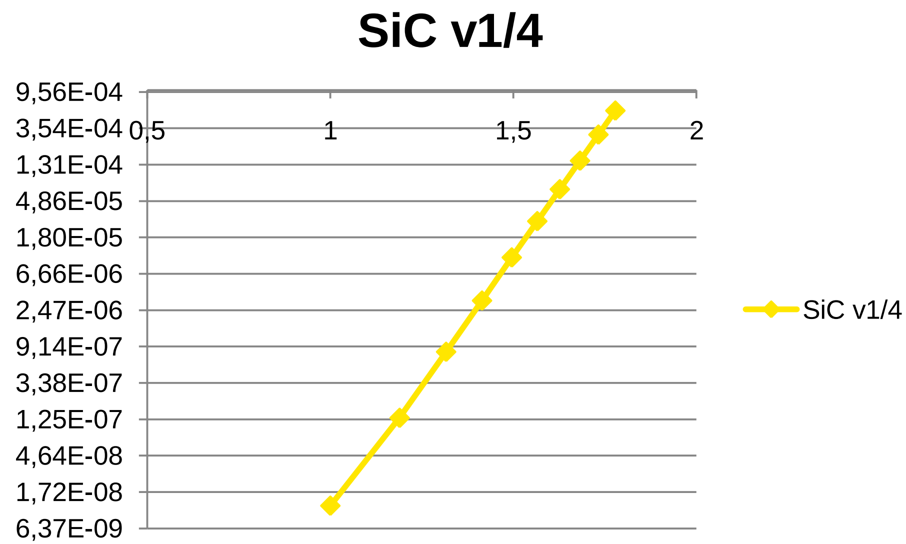
$$I_r \propto \exp\left(V^{1/2}\right)$$

    - Recombination current

$$\mathrm{I_r} \propto \mathrm{V}^{1/2}$$

# Reverse current for a SiC Schottky diode



# Current voltage characteristics

- Activation energy plot

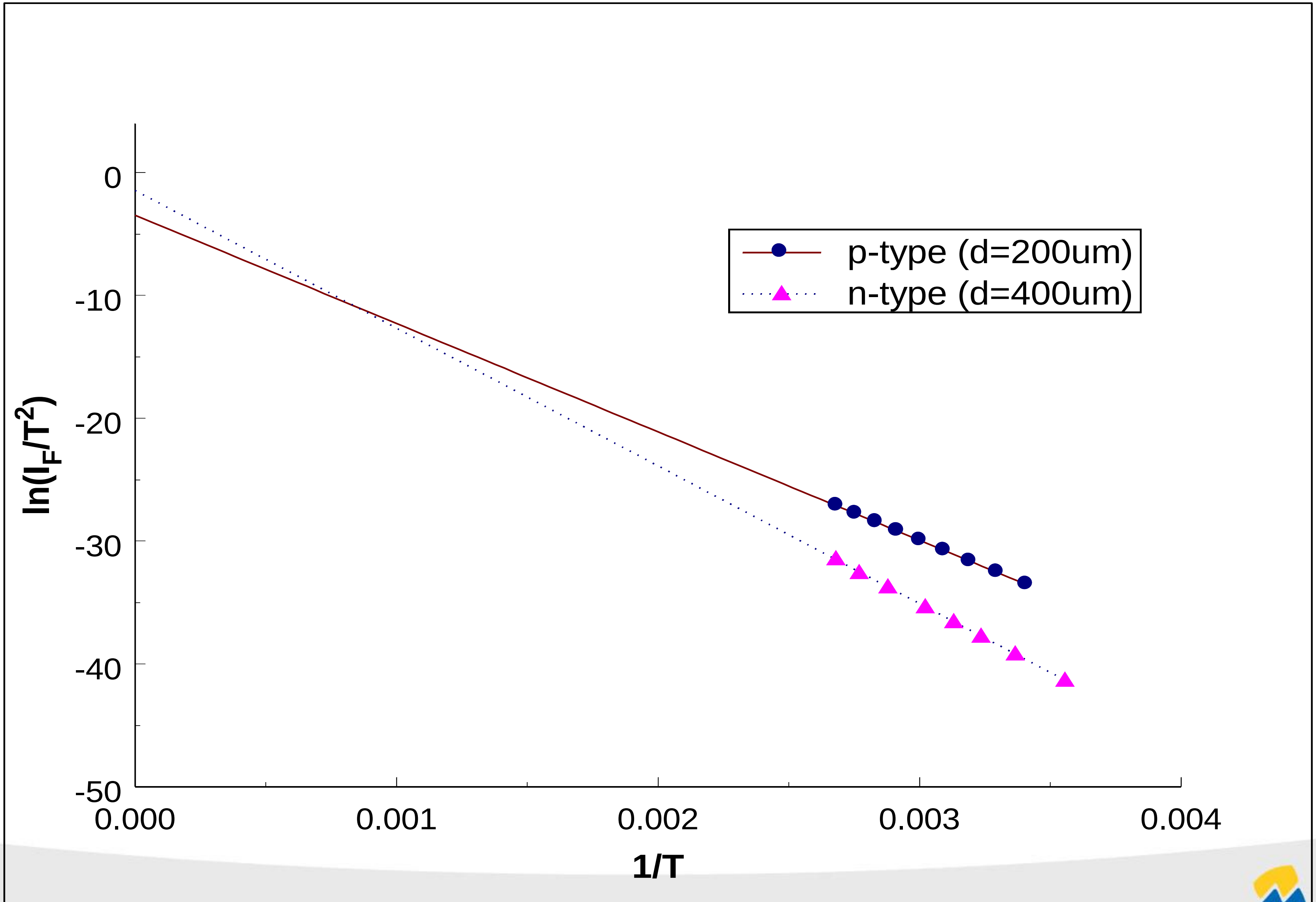
$$\ln\left(\frac{I_F}{T^2}\right) = \ln\left(SA^*\right) + \frac{1}{T}\frac{q}{k}\left(V - \Phi\right)$$

- Barrier height calculated from slope of a plot of $\ln(I_F/T^2)$ vs. $1/T$

- SA* calculated from intercept with $\ln(I_F/T^2)$ axis

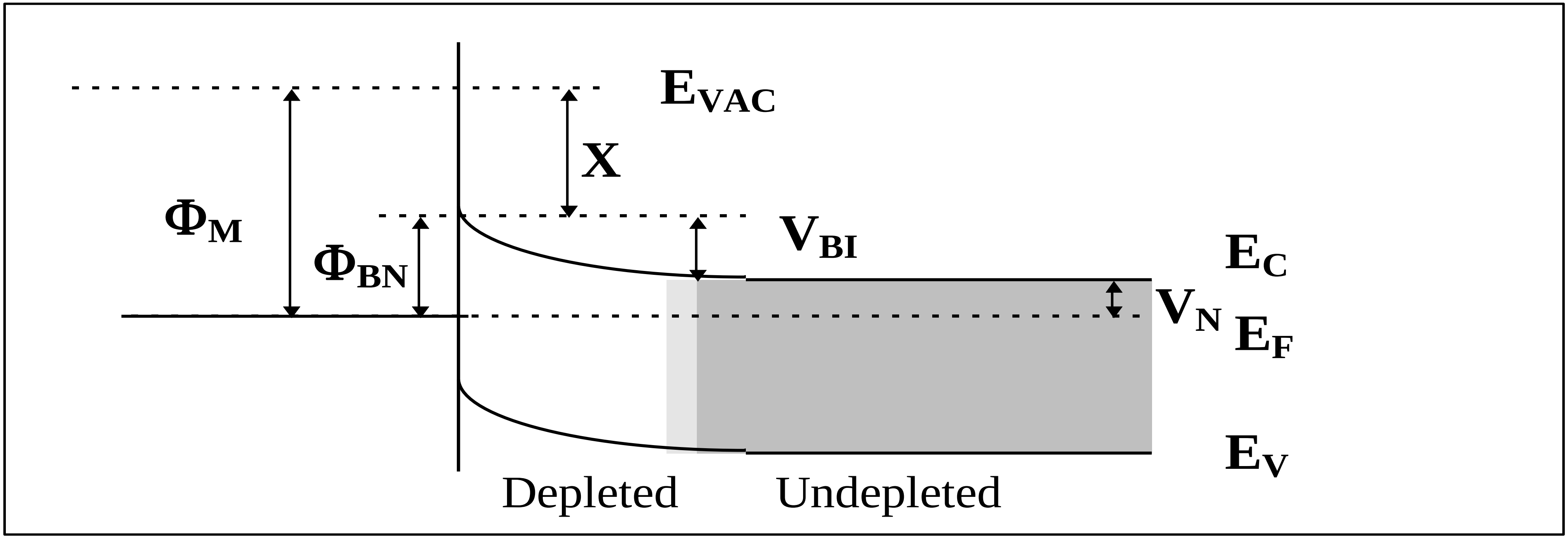
- Two methods to measure:
  1. Vary temperature and keep V constant
  2. Measure saturation current at different temp.

# Current voltage characteristics



# The capacitance of a Schottky Barrier

# The capacitance of a Schottky barrier



# The capacitance of a Schottky barrier

- The parallel plate approximation

$$C = \left( \frac{q \varepsilon_s N_D}{2} \right)^{1/2} \left( V_{BI} + V_R - \frac{kT}{q} \right)^{-1/2}$$

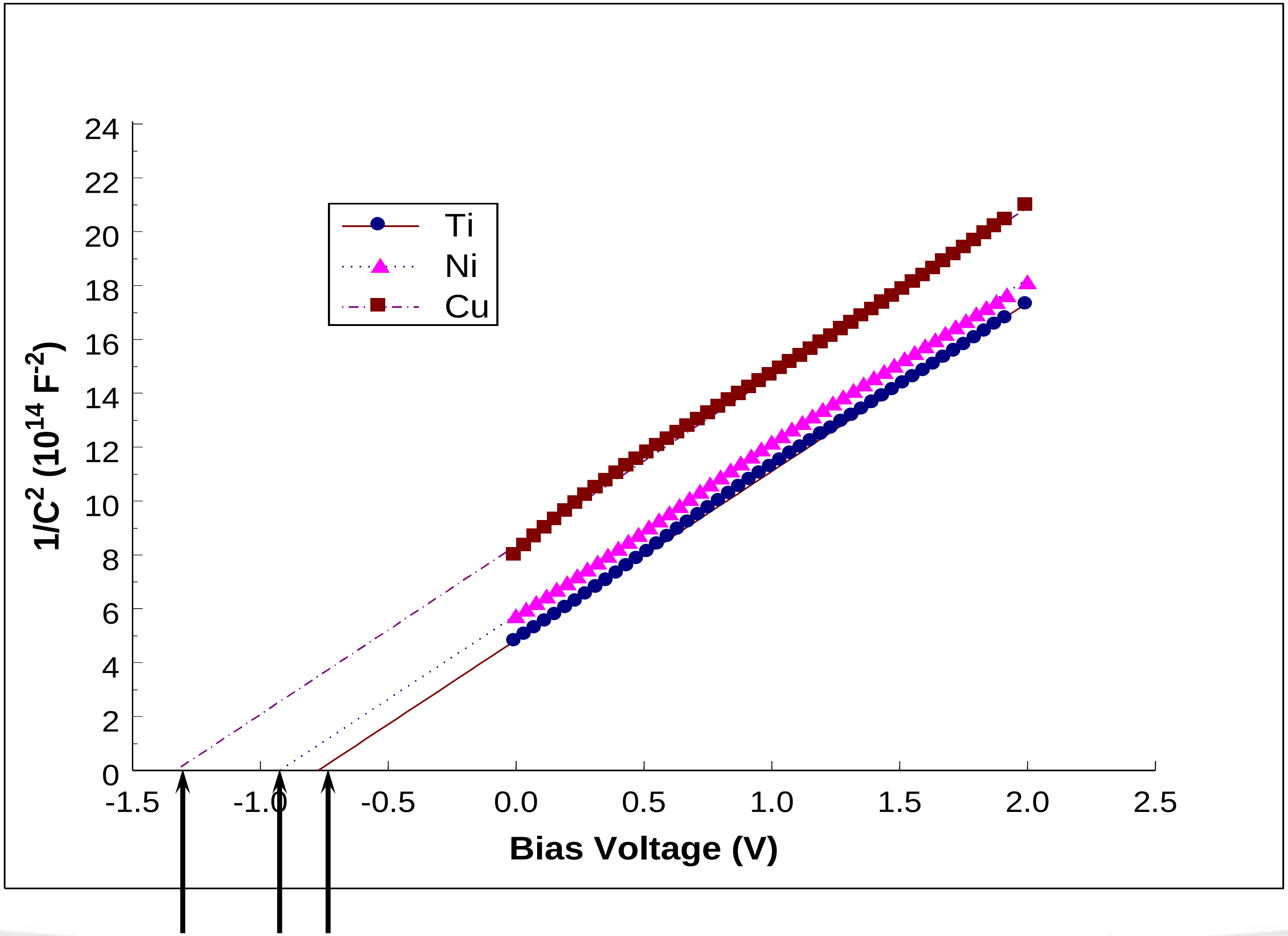
- Doping concentration

$$\frac{\mathrm{d}C^{-2}}{\mathrm{d}V_\mathrm{R}} = \frac{2}{\mathrm{q}\varepsilon_\mathrm{s}\mathrm{N}_\mathrm{D}}$$

- Barrier height

$$\Phi_B = -V_i + \frac{kT}{q}\left(1 + \ln\left(\frac{N_C}{N_D}\right)\right)$$

# The capacitance of a Schottky barrier




$V_I$ Cu Ni Ti

# The capacitance of a Schottky barrier

The expression for the barrier height is valid for a device with:

*1. Uniform doping*

*2. Completely ionized dopants*

*3. Low series resistance*

# The capacitance of a Schottky barrier

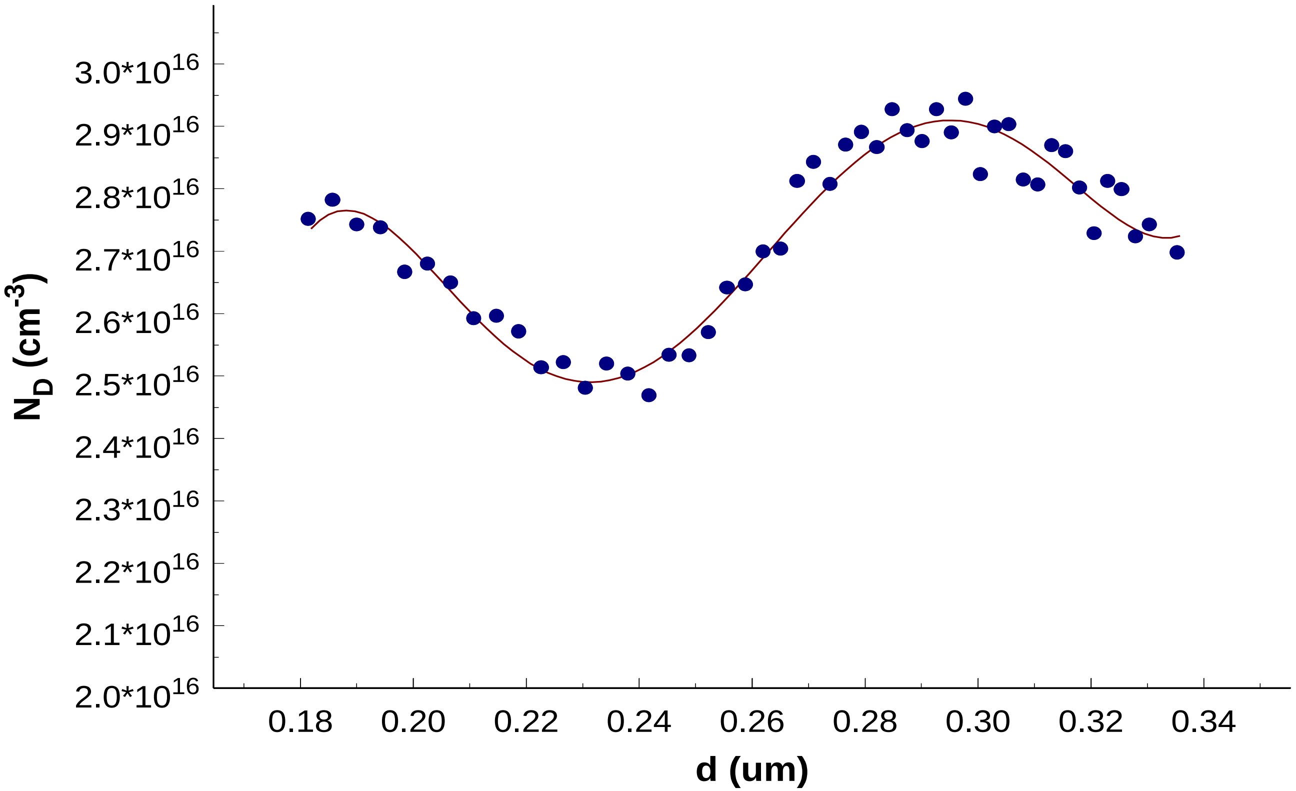
*1. Non uniform doping*

The local doping can be calculated from:

$$N(x_d) = \frac{2}{q\varepsilon_s A^2}\left(\frac{\Delta C^{-2}}{\Delta V_R}\right)^{-1}$$

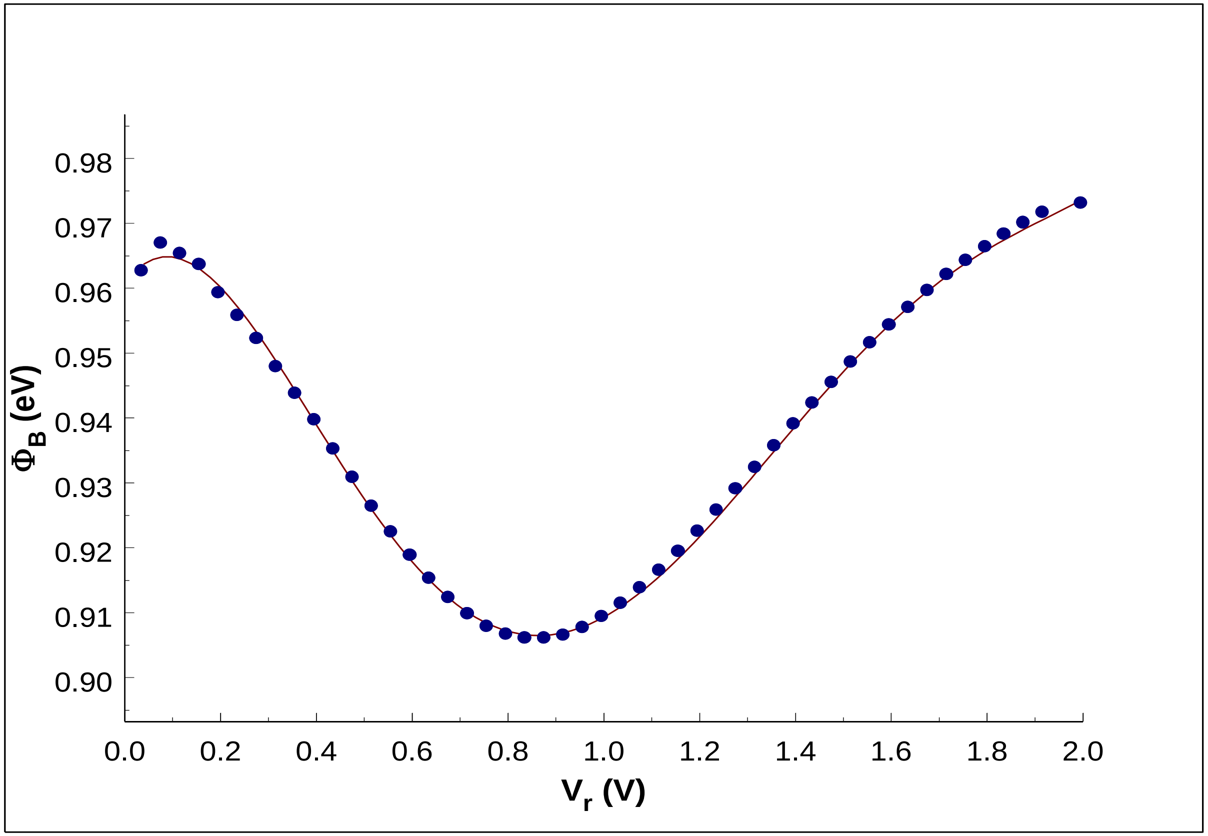
The barrier height can not be calculated

# The capacitance of a Schottky barrier
# Non uniform doping




Measured variation in the doping concentration

# The capacitance of a Schottky barrier
# Non uniform doping




Barrier height calculated from CV data for a diode on a semiconductor with non uniform doping

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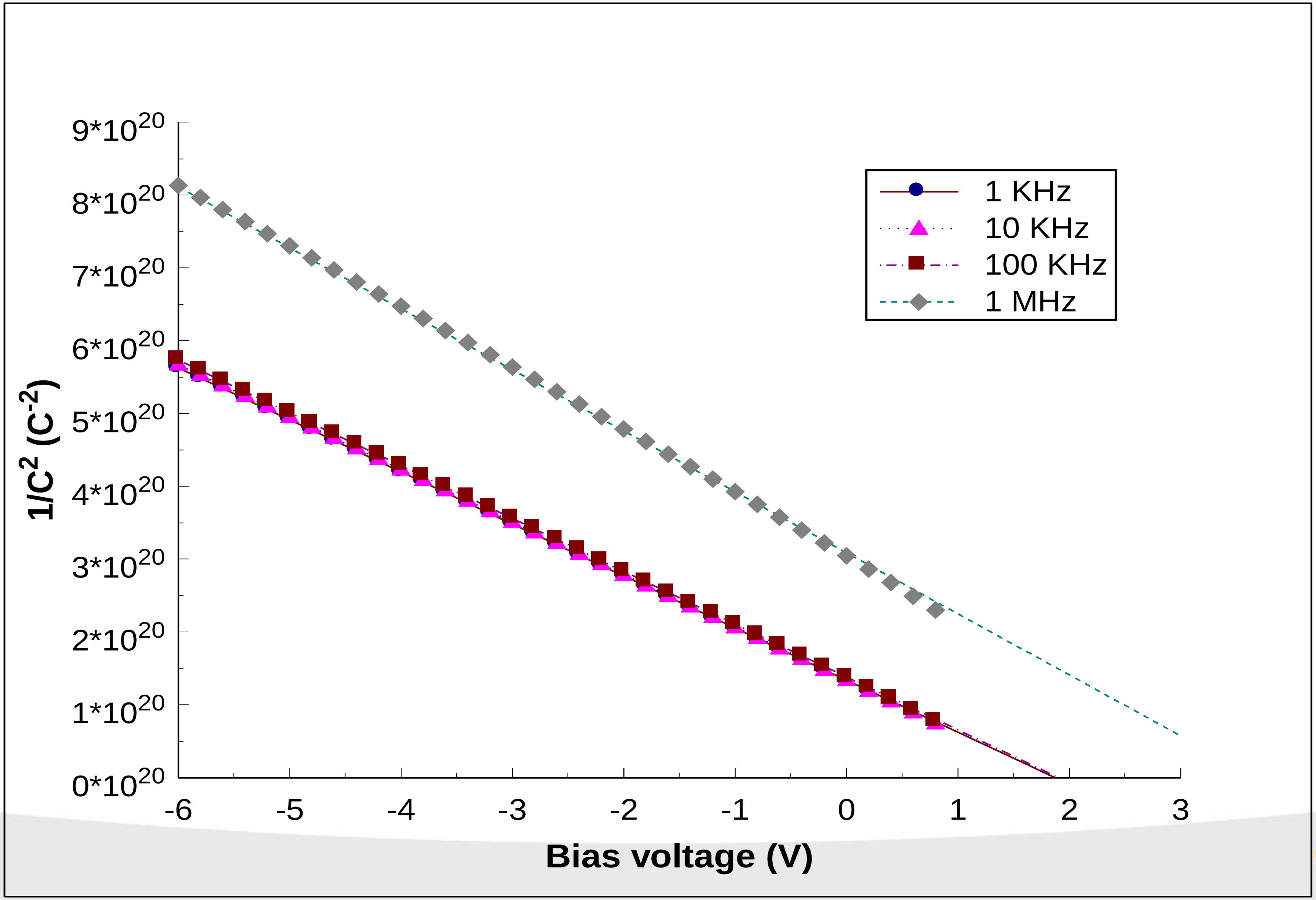
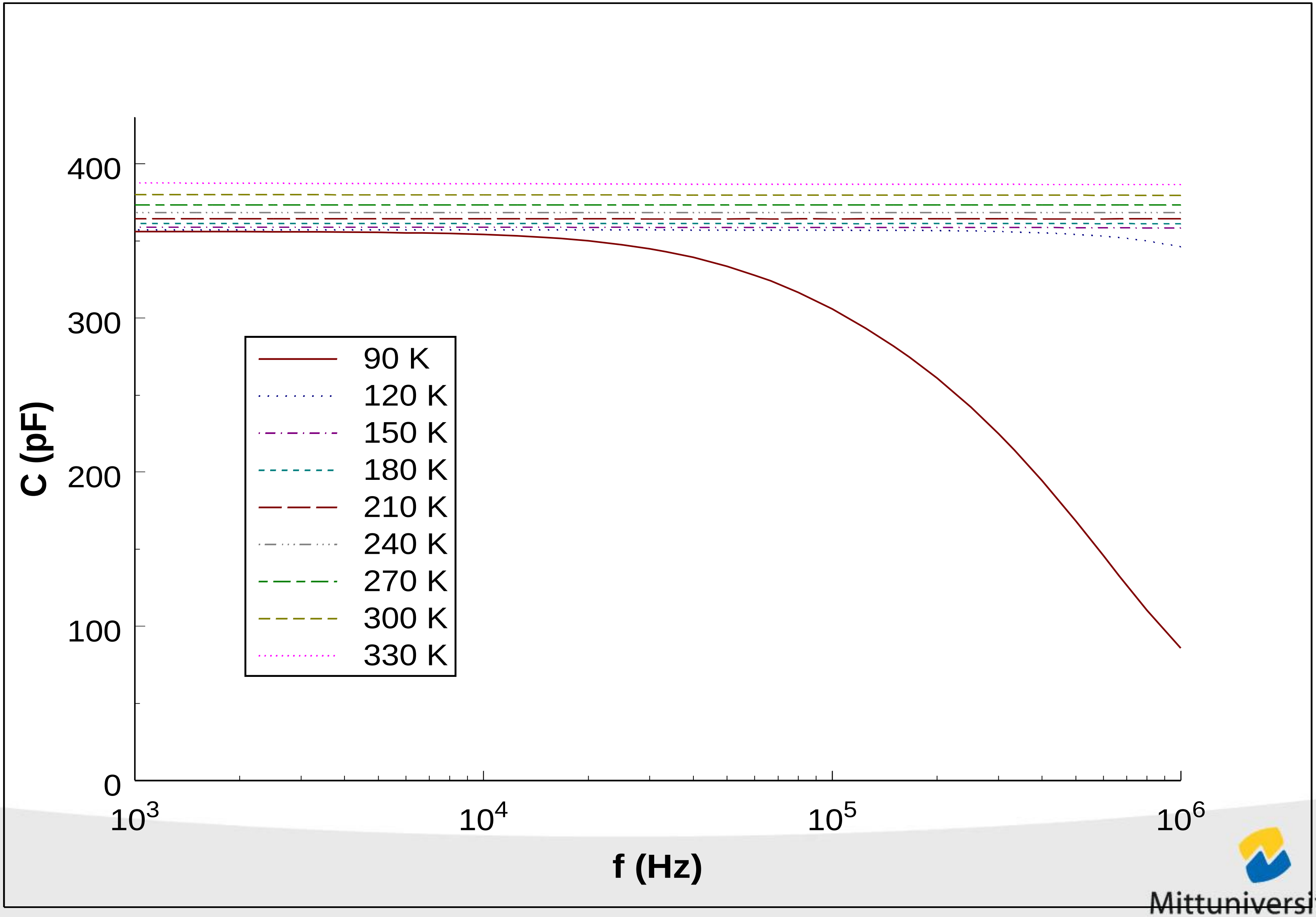
# Frequency dependence of the capacitance on p-type 6H-SiC



# Frequency dependence of the capacitance on n-type 6H-SiC

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# Photoelecteric measurements

# Photoelectric measurements

- Photoelectric excitation over the barrier according to the Fowler theory

$$R \sim (h\nu - \Phi_B)^2$$

- This expression is valid for

$$(h\nu - \Phi_B) > 3kT/q$$
$$h\nu < E_G$$

- Excitation over the bandgap has higher efficiency than Fowler excitation (~ $10^4$)

- Backside illumination reduces response from straylight

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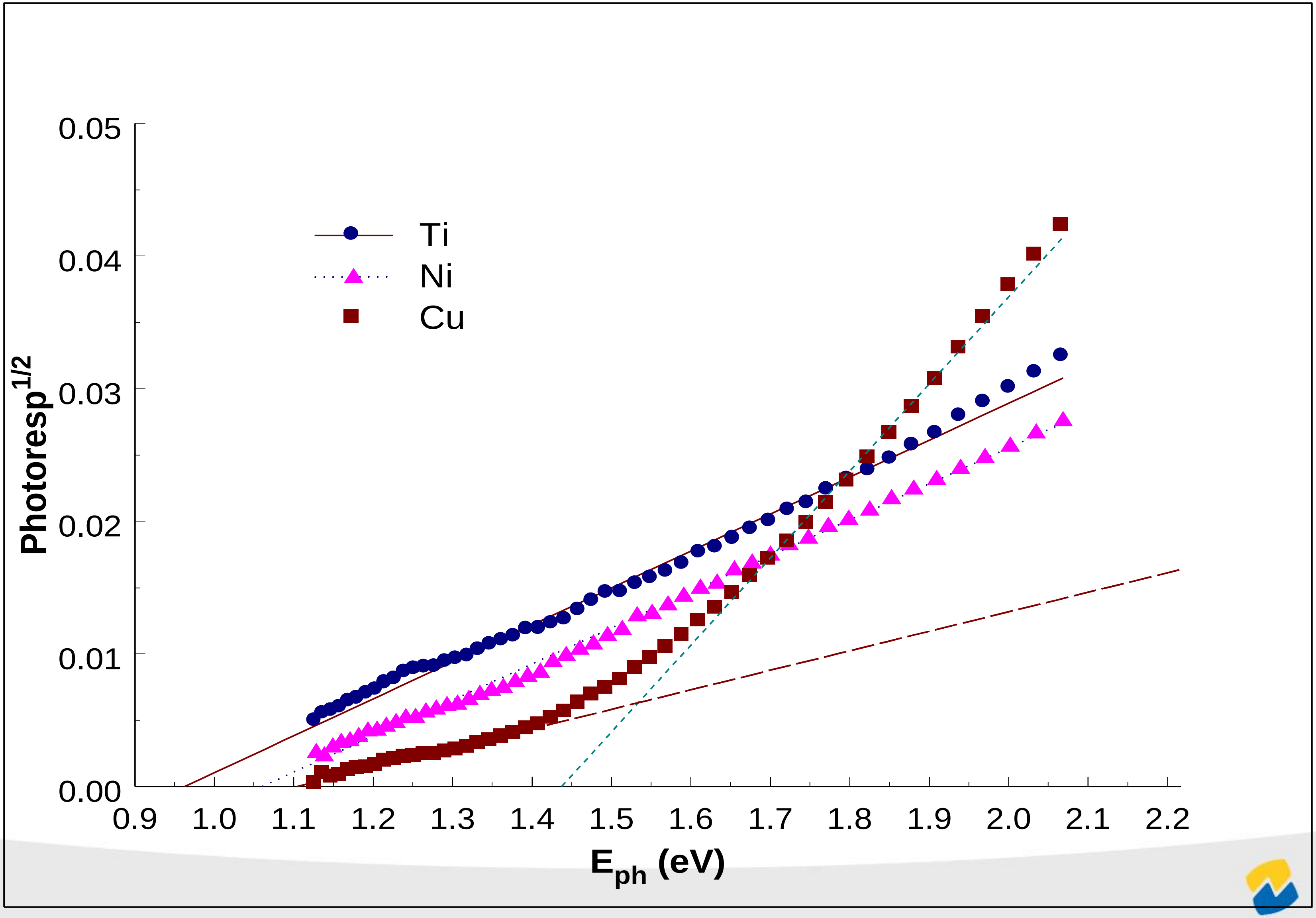
# Photoelectric measurements

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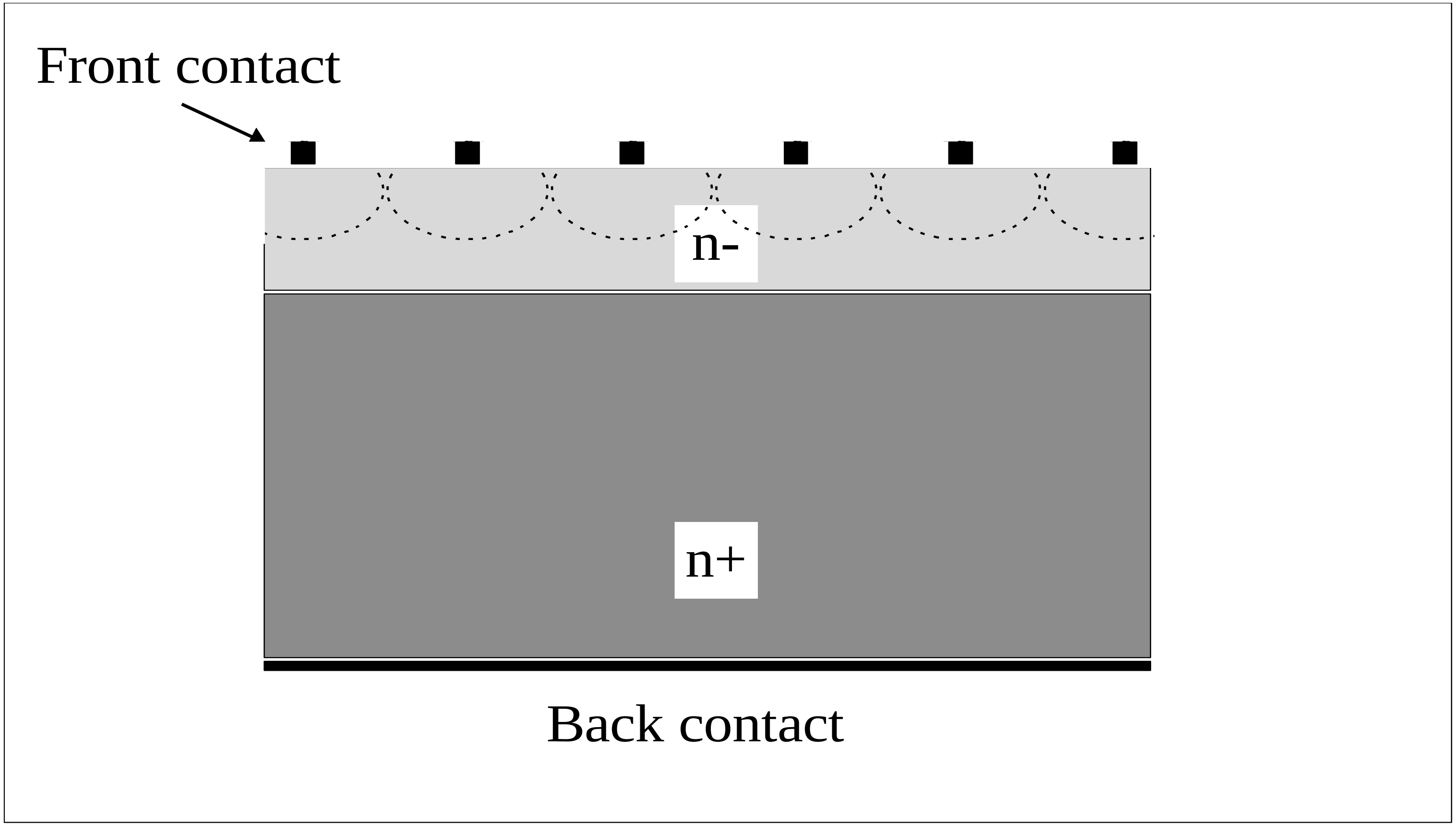
# Summary of barrier heights

| Diode | $\Phi_{BCV}$ | $\Phi_{BPHOTO}$ | $\Phi_{BIV}$ | $n_{IV}$ | $\Phi_{BACT}$ | $A^*_{ACT}$ |
|---|---|---|---|---|---|---|
| Ti-n | 0.97 | 0.98 | 0.97 | 1.03 | 0.97 | 187 |
| Ti-p | 2.04 | 2.03 | 1.85 | 1.09 | 1.96 | 113 |
| Ti-sum | 3.01 | 3.01 | 2.82 | | 2.93 | |
| Ni-n | 1.12 | 1.06 | 1.08 | 1.06 | | |
| Ni-p | 1.34 | 1.86 | 1.67 | 1.34 | | |
| Ni-sum | 2.46 | 2.92 | 2.75 | | | |
| Cu-n | 1.52 | 1.44 | 0.95 | 1.03 | | |
| Cu-p | 1.22 | 1.60 | 1.36 | 1.13 | | |
| Cu-sum | 2.74 | 3.04 | 2.31 | | | |

# Schottky photo diodes in 6H-SiC

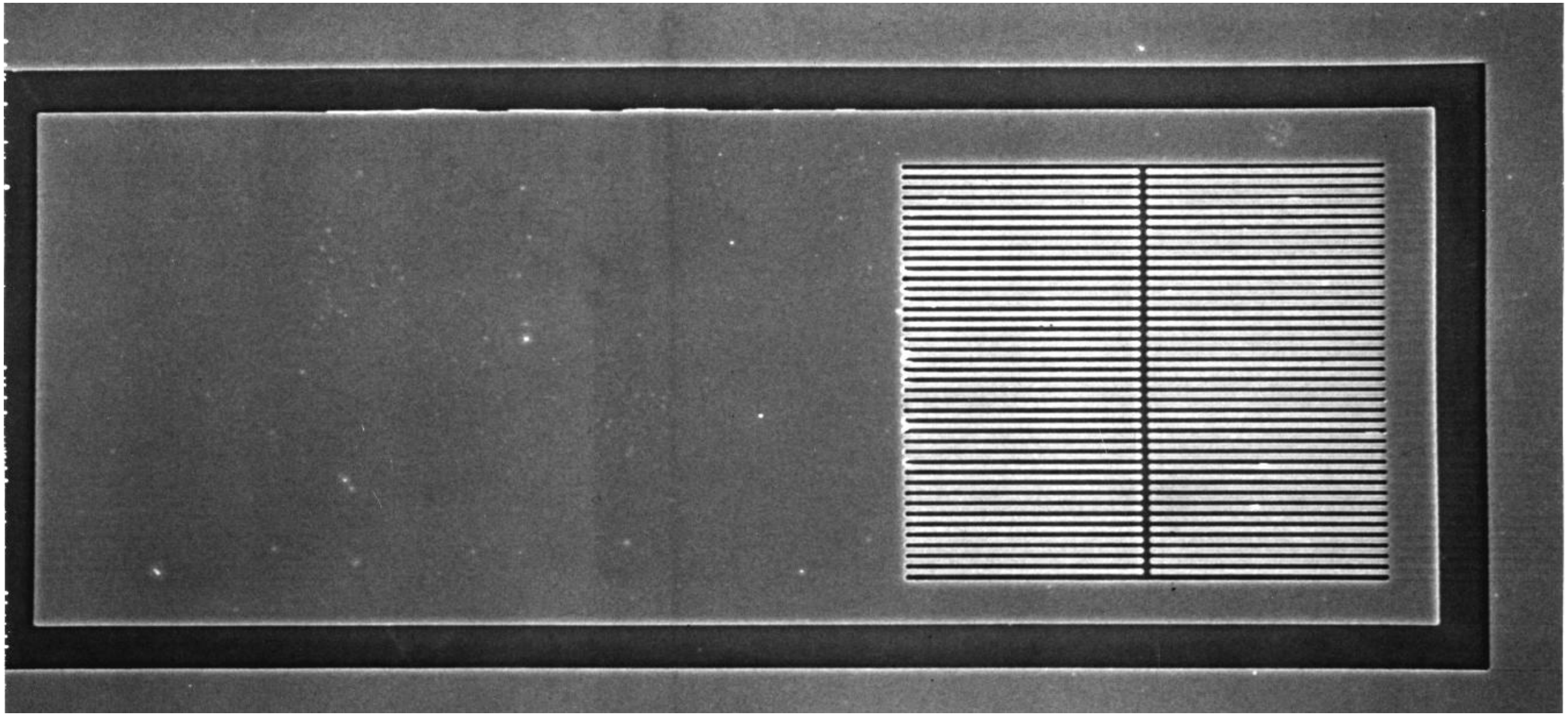
- Ti based Schottky diodes on n-type and p-type 6H-SiC
  - Finger shaped structure
  - Different doping on n-type
- Electrical characterization
  - Barrier height
  - Forward current
  - Reverse current
- Photoelectric characterization
  - Relative spectral response
  - Comparison of response for different devices
- Simulation of the expected response

# Schottky photo diodes in 6H-SiC



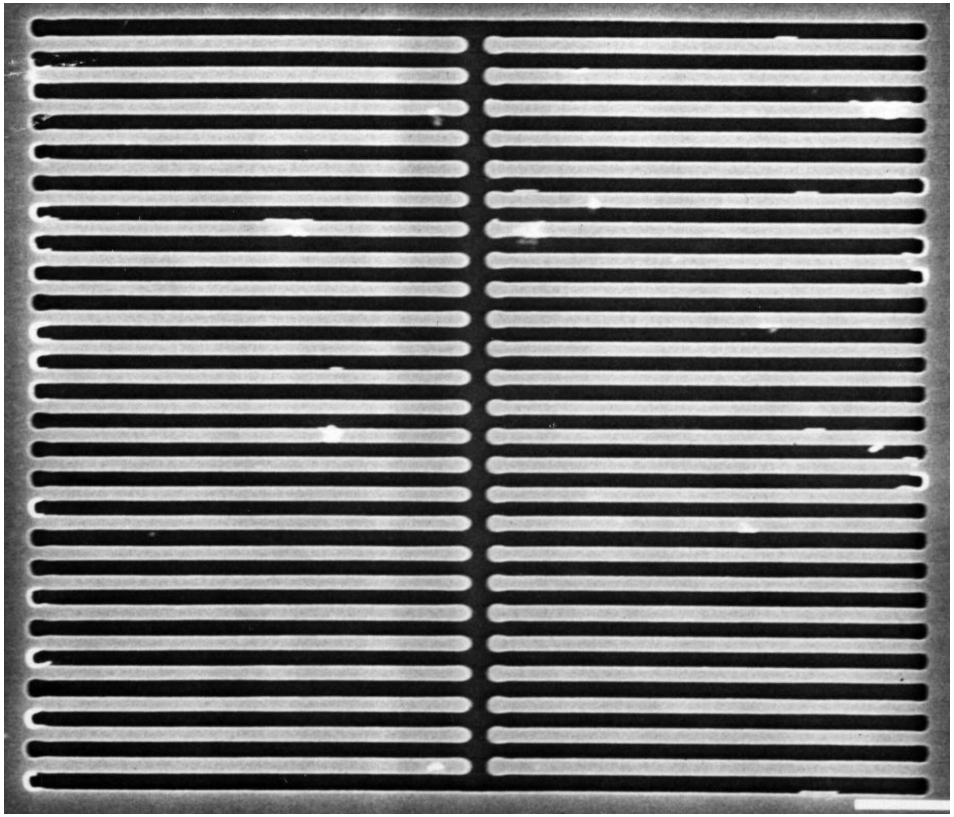

- No dead top layer, only surface recombination
- Loss of active area due to the fingers

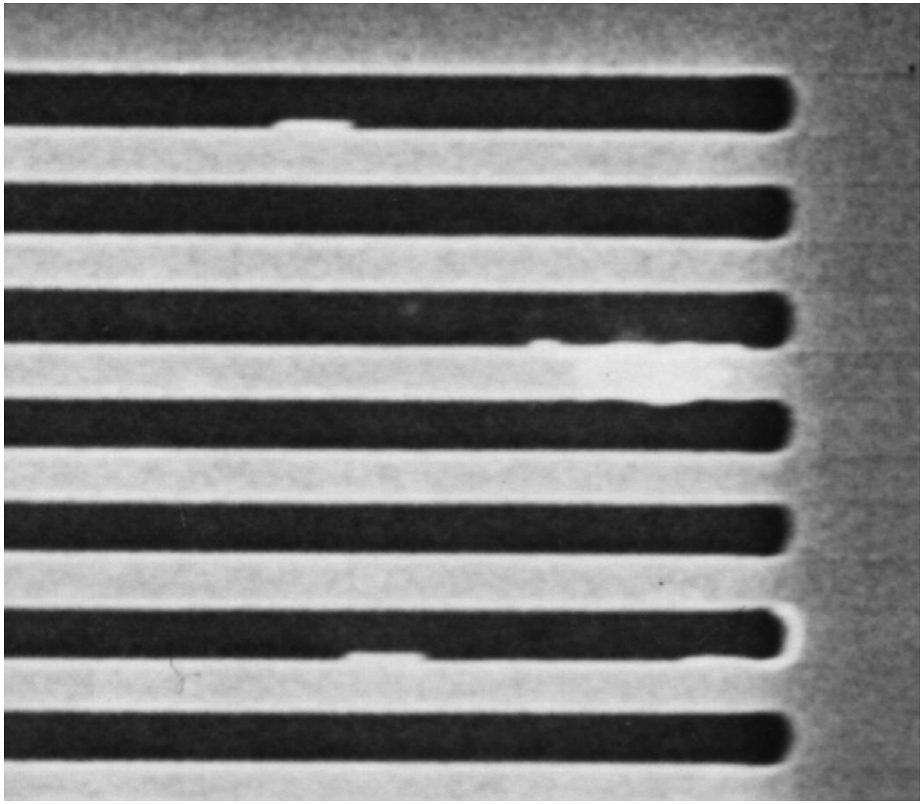
# The mask



- Cell area: 120 x 220 $\mu m^2$
- Device area: 100 x 100, 75 x 75, 50 x 50, 25 x 25 $\mu m^2$
- Border width: 10 $\mu m$

# The mask





- Finger width: 0.6 - 2.0 μm
- Finger length: 100, 75, 50, 25 μm

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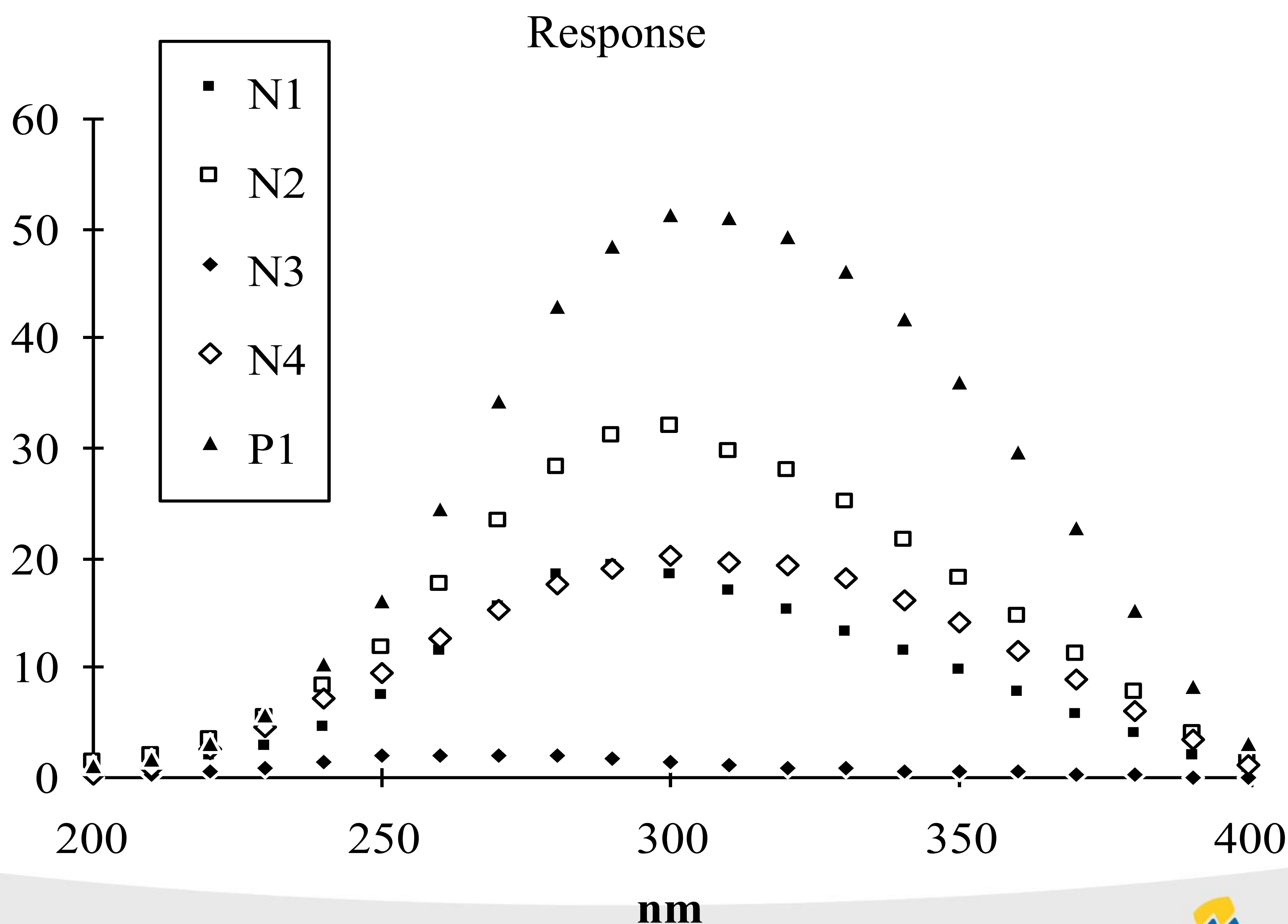
# Electrical characteristics

| | $N_D(N_A)$ | **ΦB CV** | **ΦB IV** | **N** | **Ir@ - 10V** |
|---|---|---|---|---|---|
| **N1** | $7.5*10^{15}$ | 0.98 | 0.97 | 1.08 | < 10 pA |
| **N2** | $2.9*10^{16}$ | 0.89 | 0.92 | 1.14 | 0.4 nA |
| **N3** | $2.7*10^{18}$ | 0.94 | 0.79 | 1.23 | 0.5 mA |
| **N4** | $1.0*10^{17}$ | 0.94 | 0.84 | 1.17 | 18 µA |
| **P1** | $1.6*10^{17}$ | 2.43 | 1.94 | 1.03 | < 1 pA |

N1: Thin epitaxial layer (1.6 um)
N4: High density of visible defects

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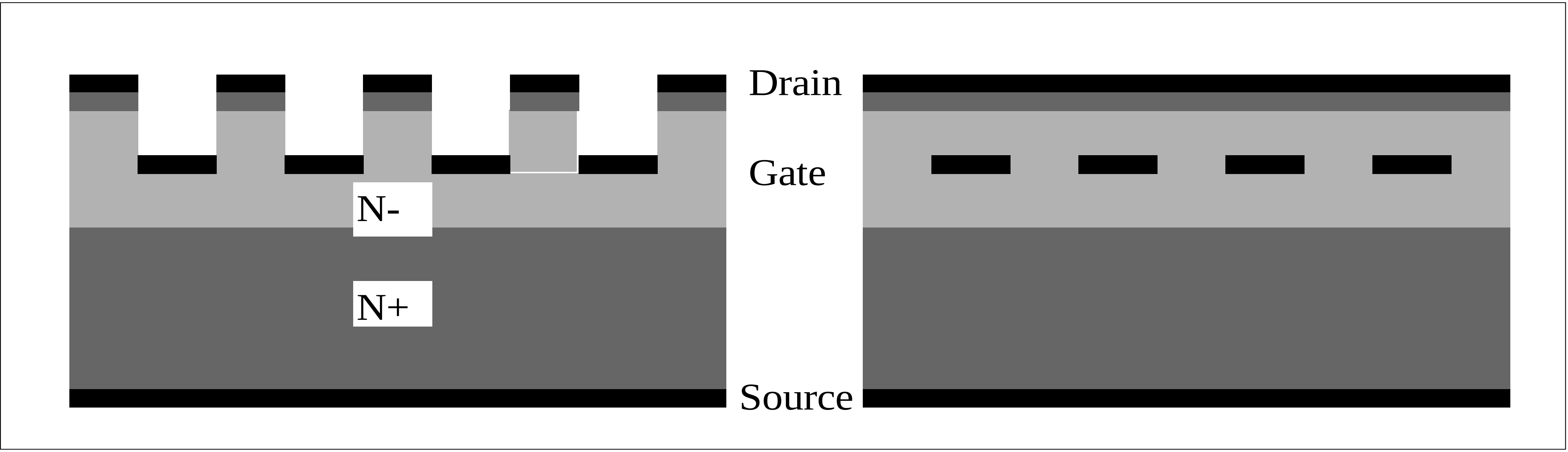
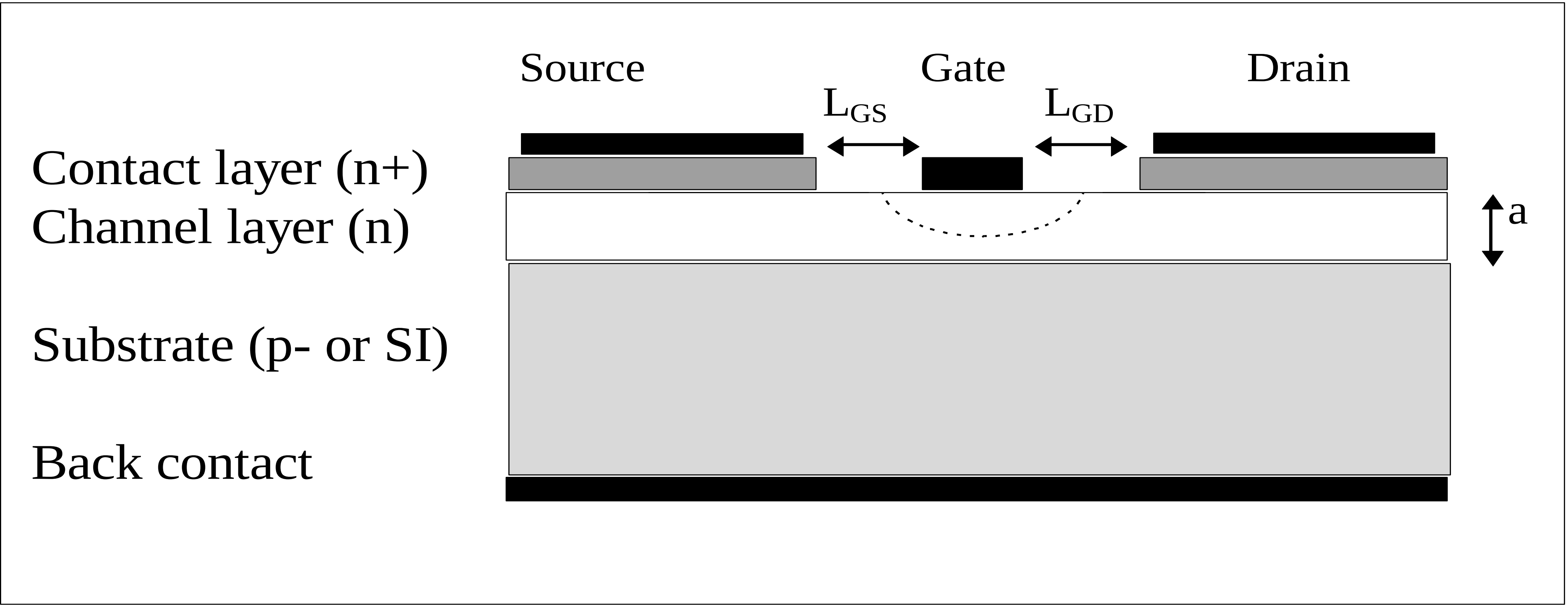
# The Permeable Base Transistor

Etched groove Overgrown

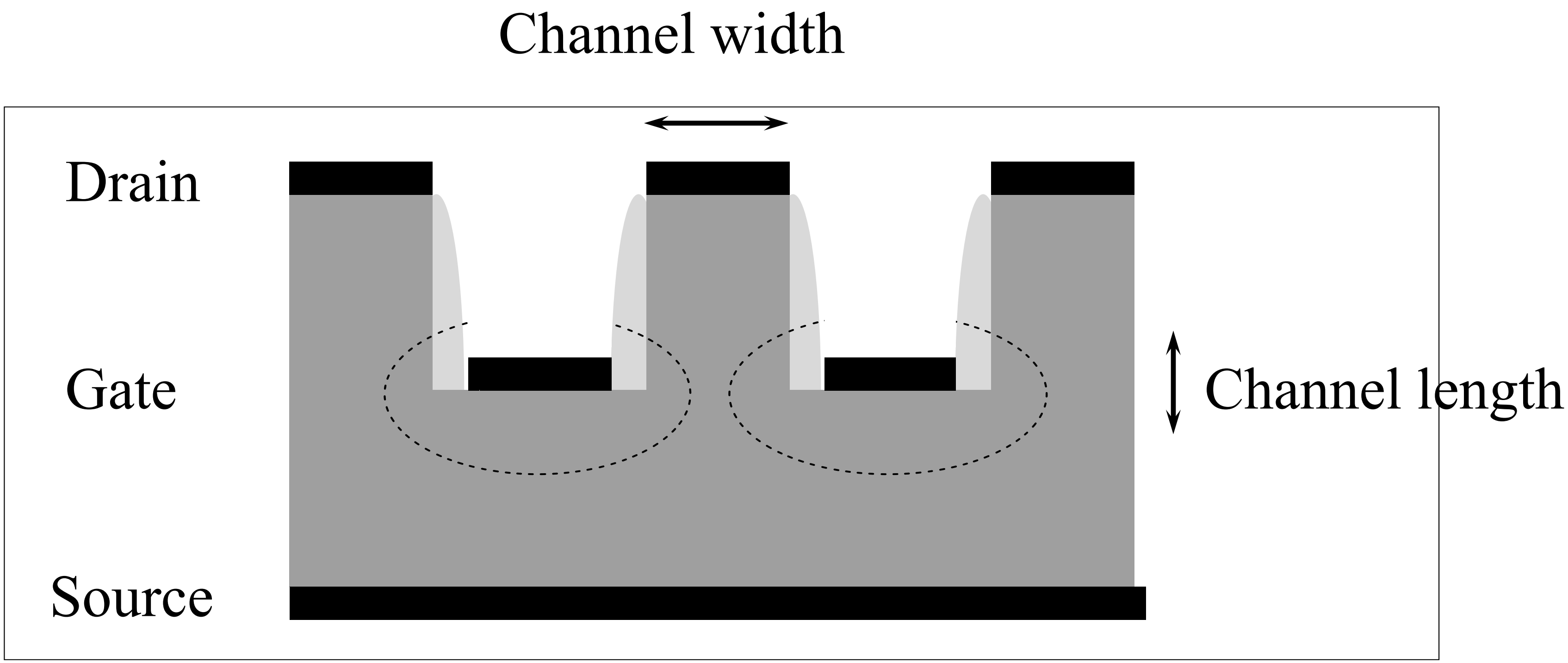



- Vertical MESFET
- Current controlled by depletion around gate

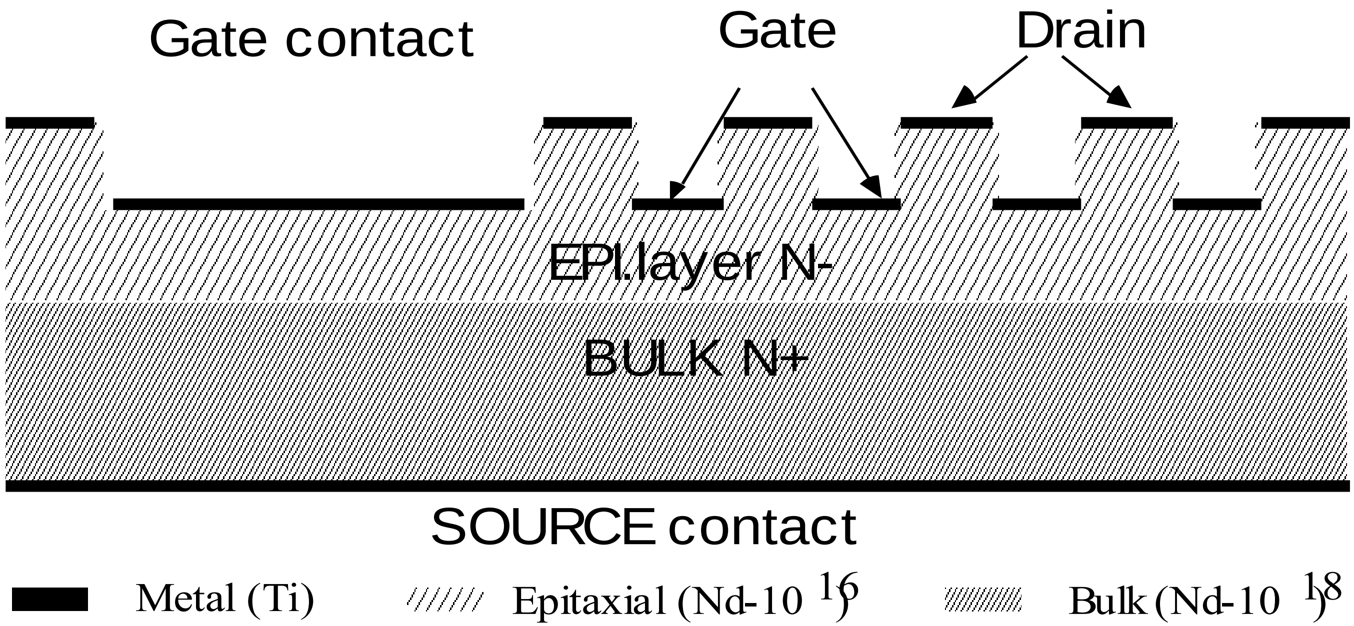
# The Horizontal Mesfet

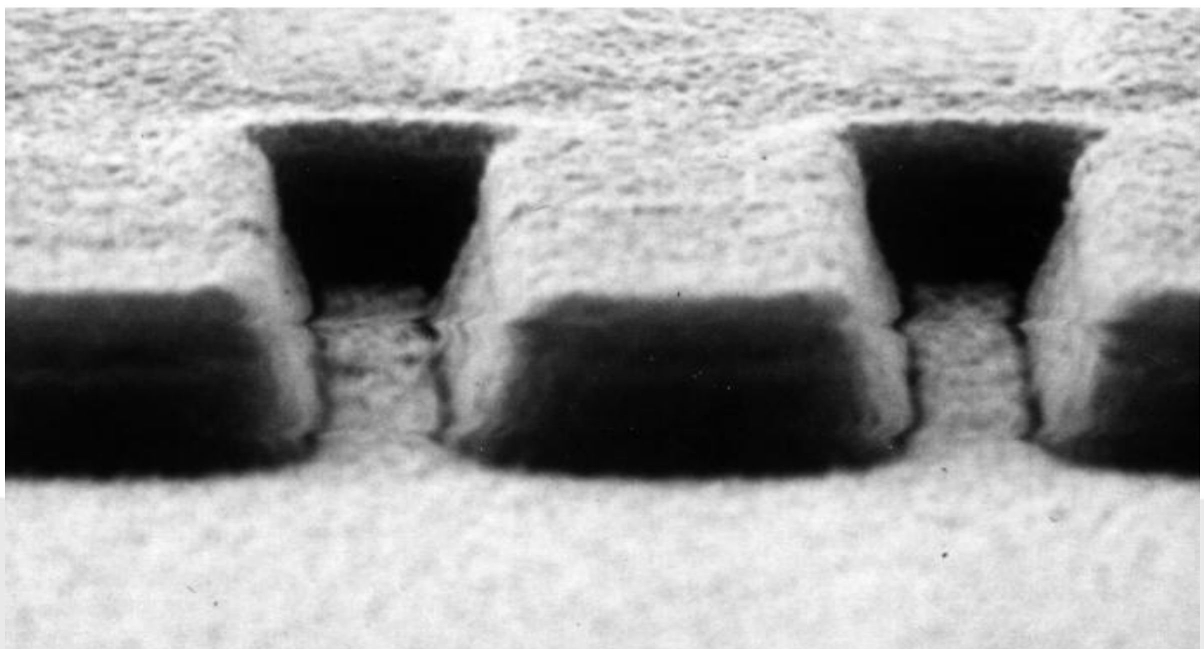


# The Permeable Base Transistor

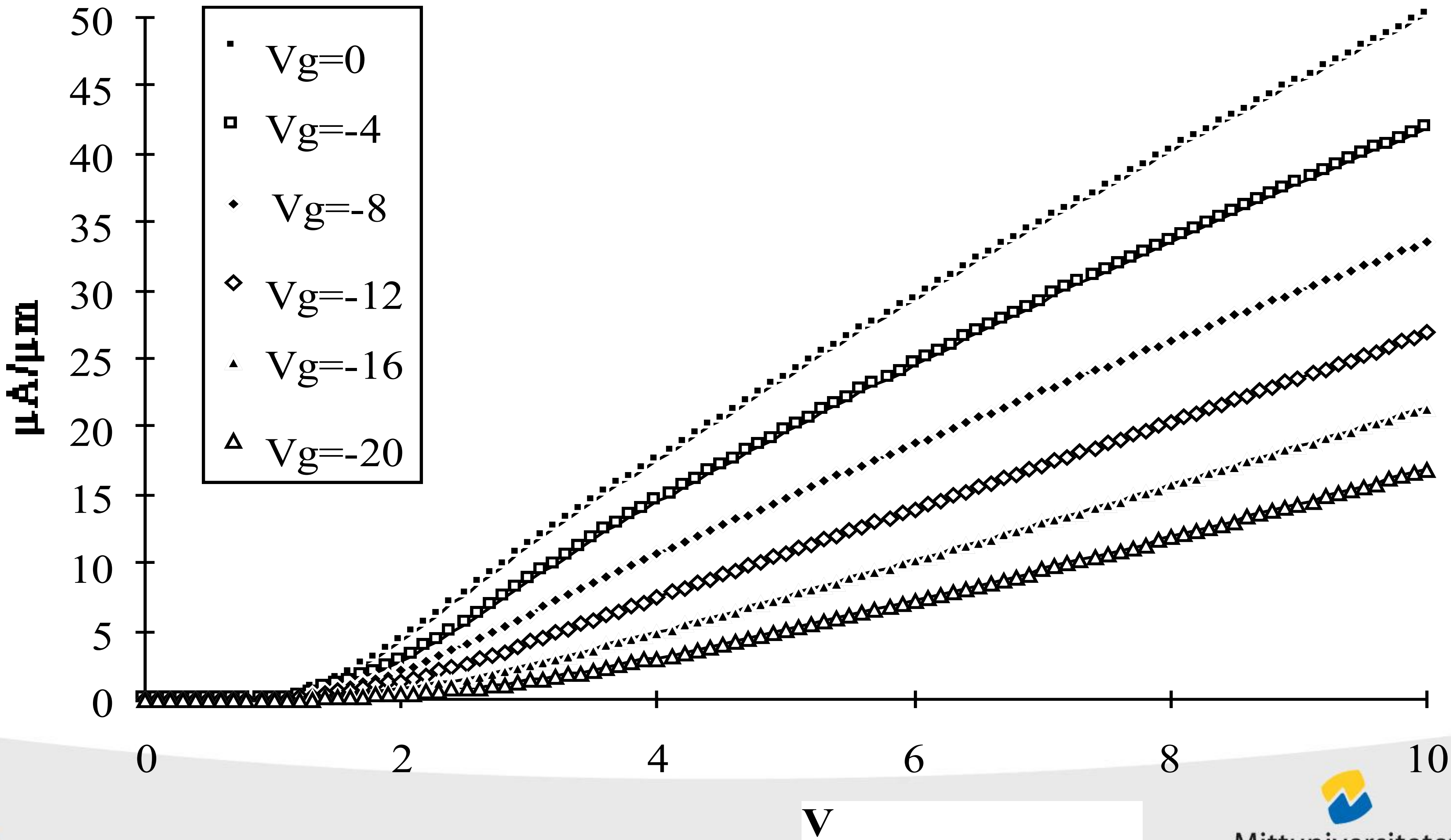


# The Permeable Base Transistor in 6H-SiC



# The Permeable Base Transistor in 6H-SiC

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