2nd Berkeley Symposium on Energy Efficient Electronic Systems

Tunnel Transistor Mechanism Based on Density of States Switching

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M&E TECH

The New Switch has to Satisfy Three Specifications:

1. Steepness (or sensitivity)

switches with only a few milli-volts

60mV/decade ⇒ **1mV/decade**

2. On/Off ratio. $10^6 : 1$

3. Current Density or Conductance Density

(for miniaturization)

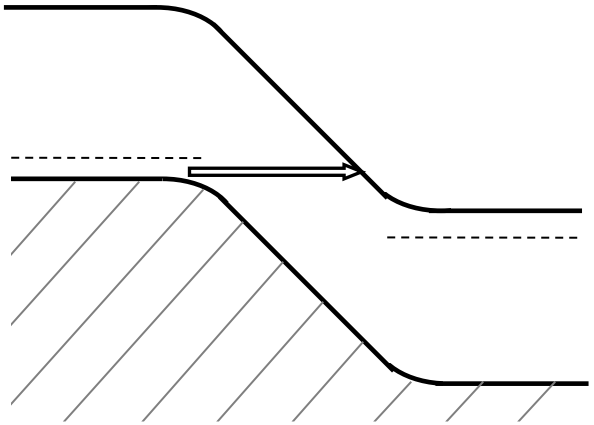
old spec at 1Volt: 1 mAmp/micron

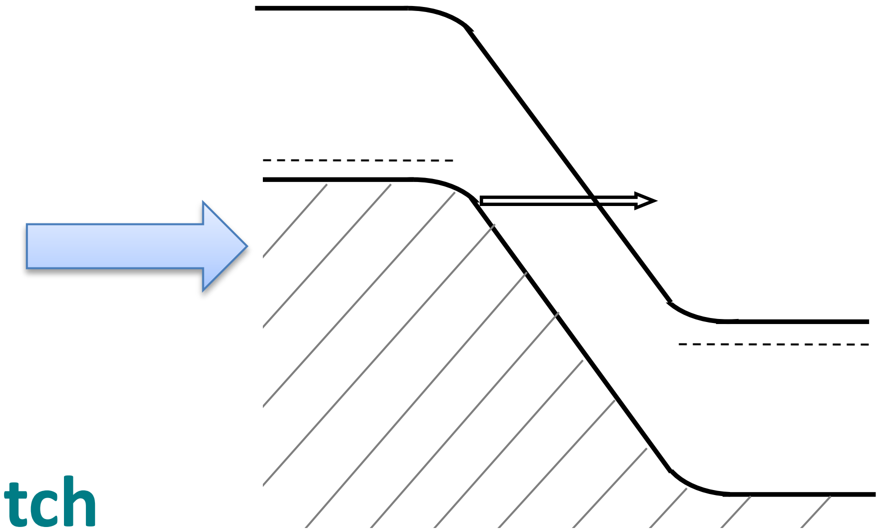
our spec: **1 milli-mho/micron**

A 1 micron device should conduct at 1KΩ in the on-state.

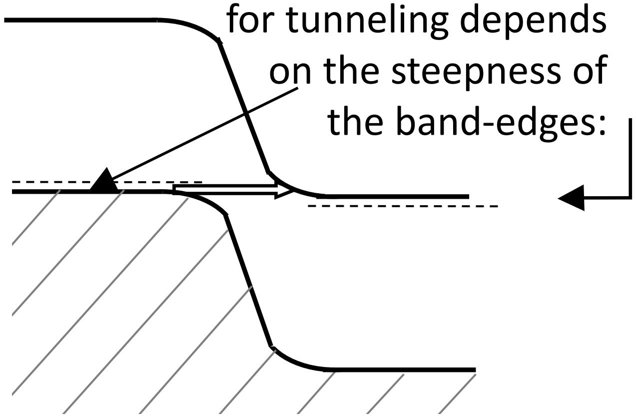
2 Ways to Obtain Steepness

- **Modulate the Tunneling Barrier**



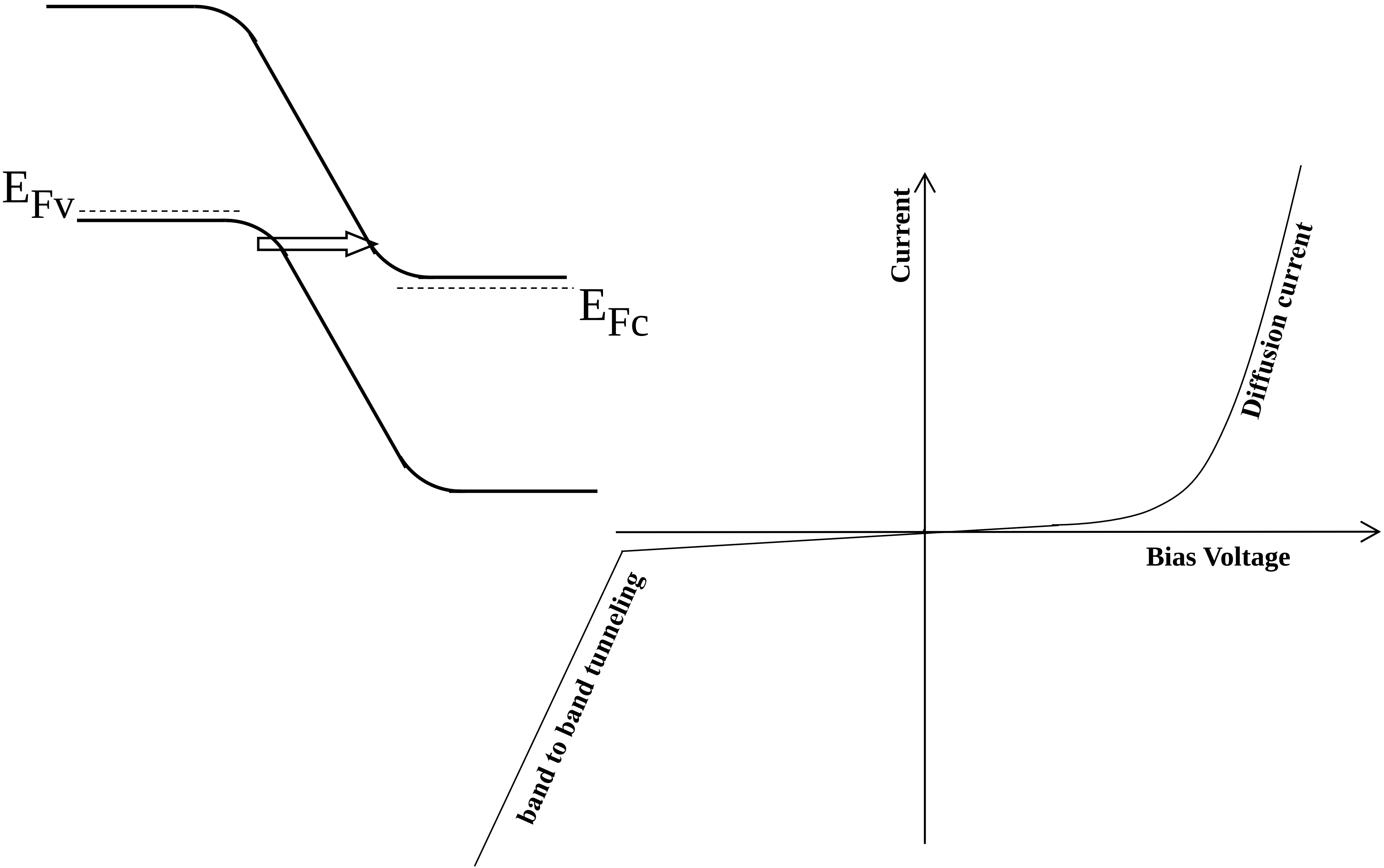


- **Density of States Switch**

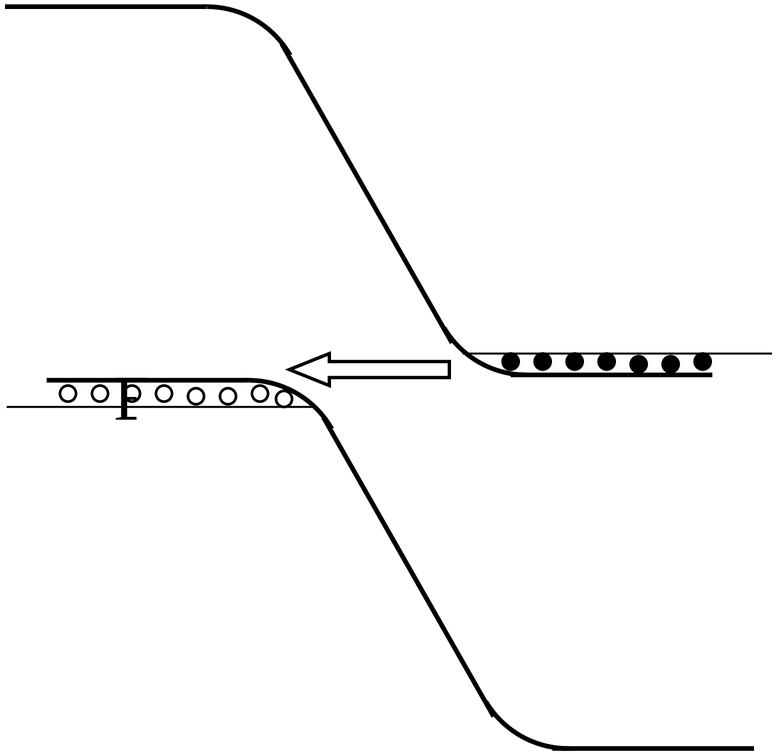


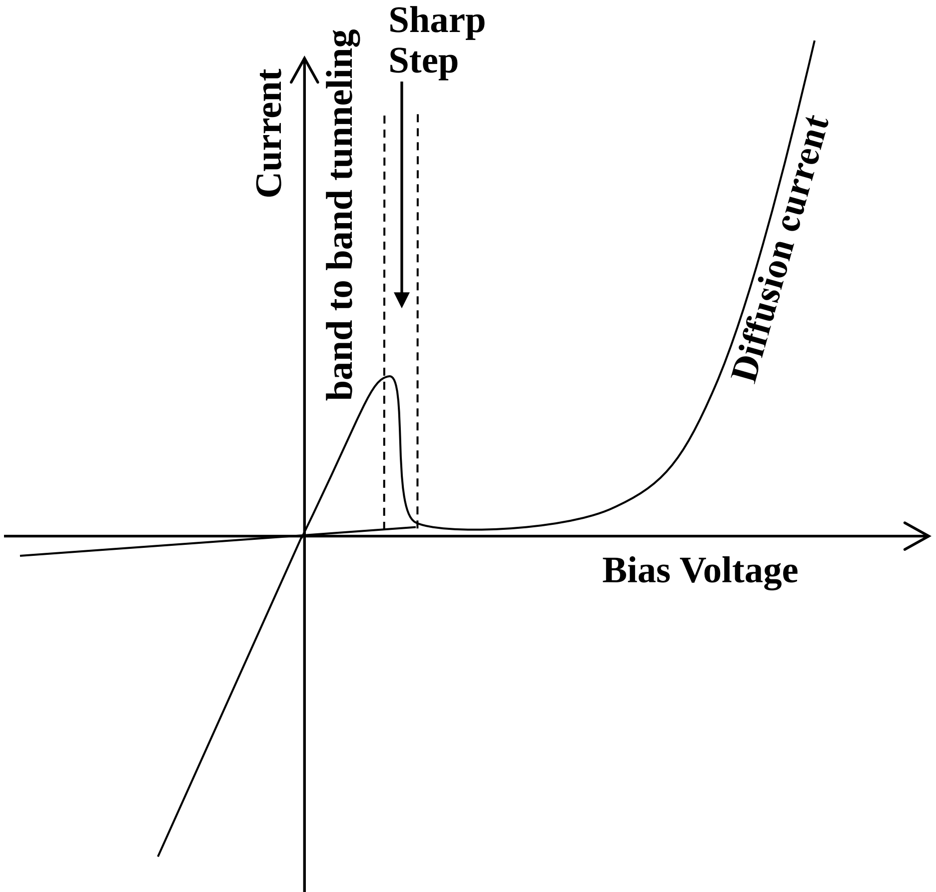
The sub-threshold slope
for tunneling depends
on the steepness of
the band-edges:

The Zener Diode:



The Esaki Diode:

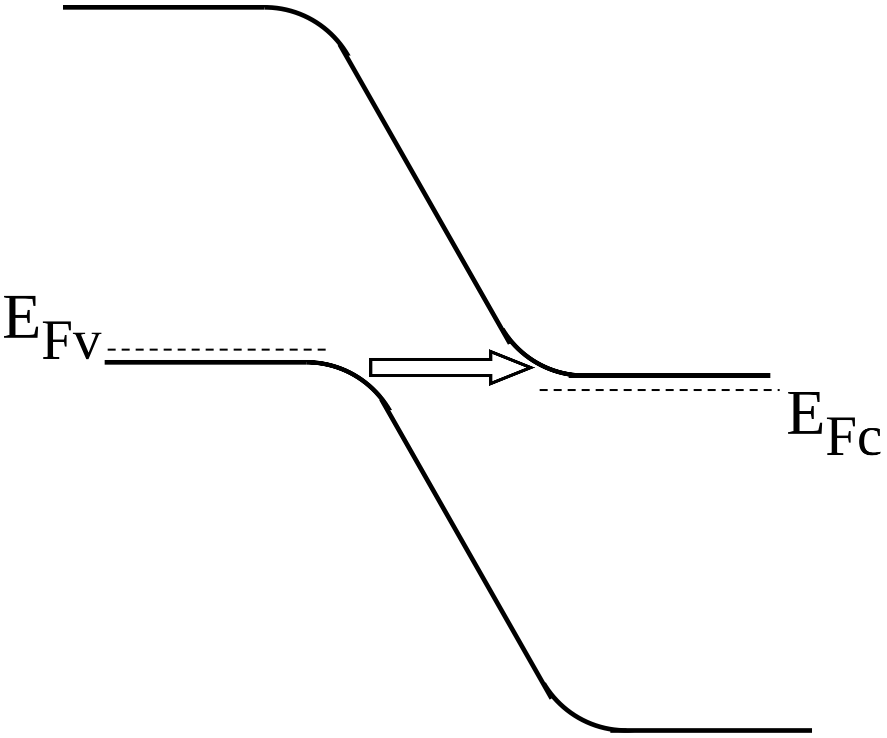


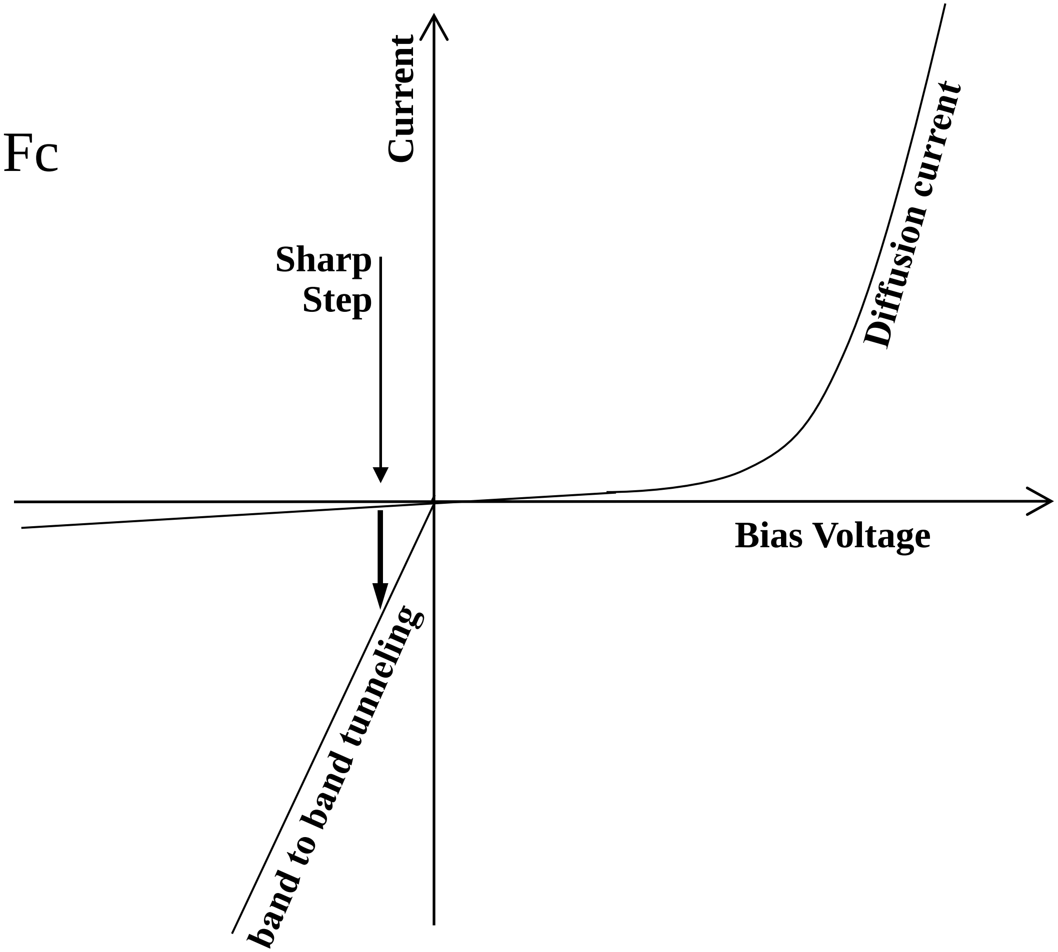


The Backward Diode as a Switch:

The Backward Diode:

These have been routinely made in Ge homo-junctions, since the 1960's.





Sb-Heterostructure Interband Backward Diodes

J. N. Schulman and D. H. Chow

***Abstract*—Backward diodes are a version of Esaki tunnel diodes that are useful for mixing and detection. Ge backward diodes in particular have been used as temperature insensitive, zero bias square law detectors, capable of translating low level rf power into dc voltage or current with extreme linearity and low noise. However, Ge diodes are difficult to reproducibly manufacture and are physically fragile. Here we demonstrate specially designed Sb-heterostructure-based backward diodes grown by molecular beam epitaxy. These diodes have superior figures of merit compared to Ge diodes, especially the current density and junction resistance, and are reproducible and physically rugged. In addition, the flexibility of MBE growth allows easy tailoring of the layer structure to maximize the desired figure of merit for a given application.**

***Index Terms*—Millimeter wave detectors, millimeter wave diodes, milimeter wave imaging, millimeter wave mixers, semiconductor heterojunctions, tunnel diodes, tunneling.**

I. INTRODUCTION

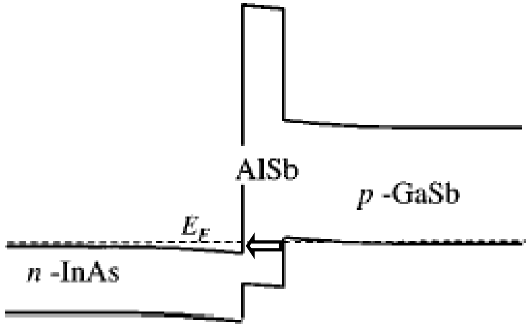
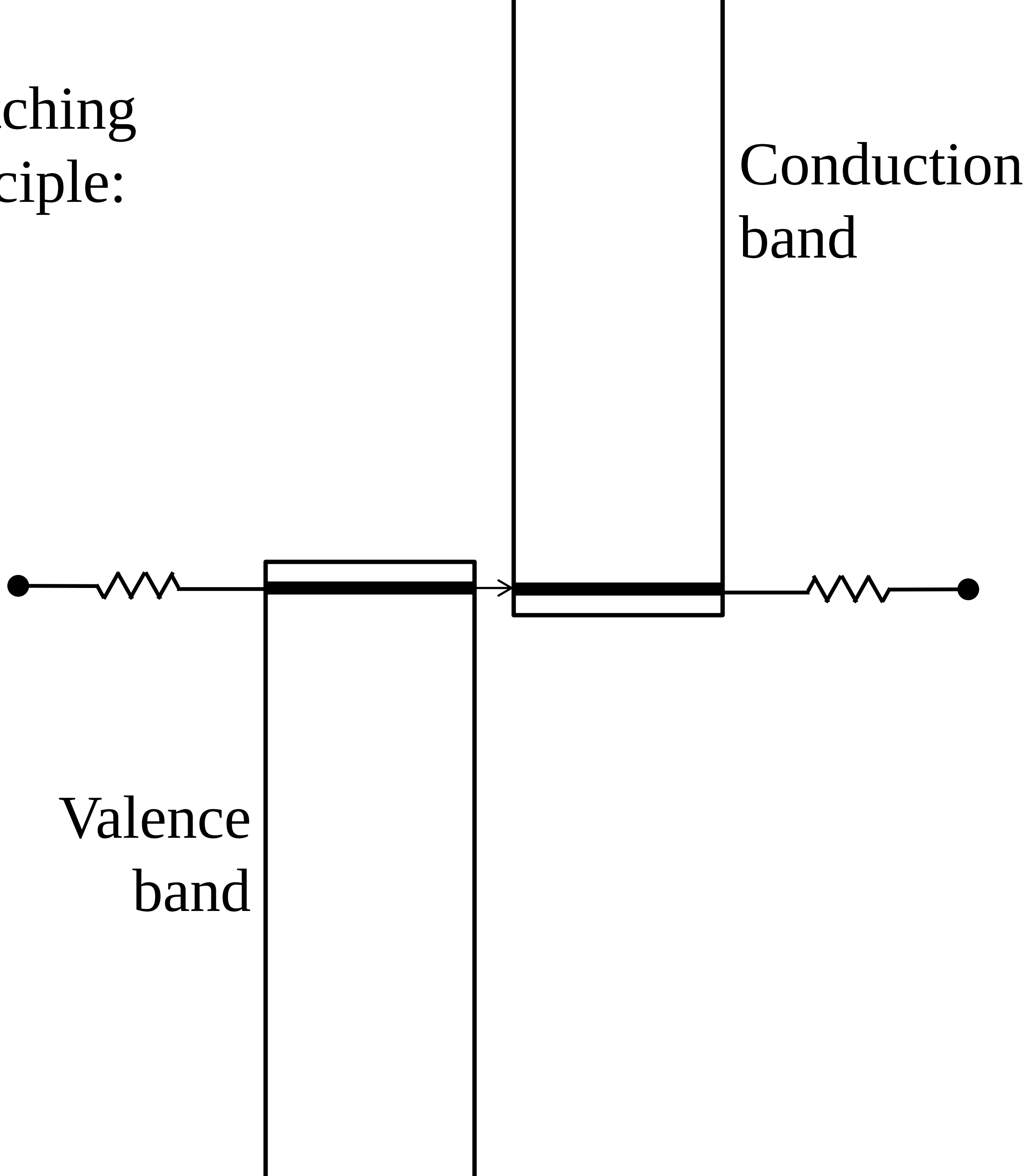


Fig. 1. Band diagram of InAs/AlSb/GaSb diode.

technology is relatively primitive and reproducibility is a challenge [2] as modern epitaxial growth techniques have not been sufficiently developed for Ge. Perhaps as serious a problem is that Ge diodes cannot withstand ordinary soldering processes making packaging difficult. Modern epitaxial growth technology has provided new avenues for exploring substitutes for Ge, including GaAs/AlGaAs [3] and InGaAs [4] alternatives.

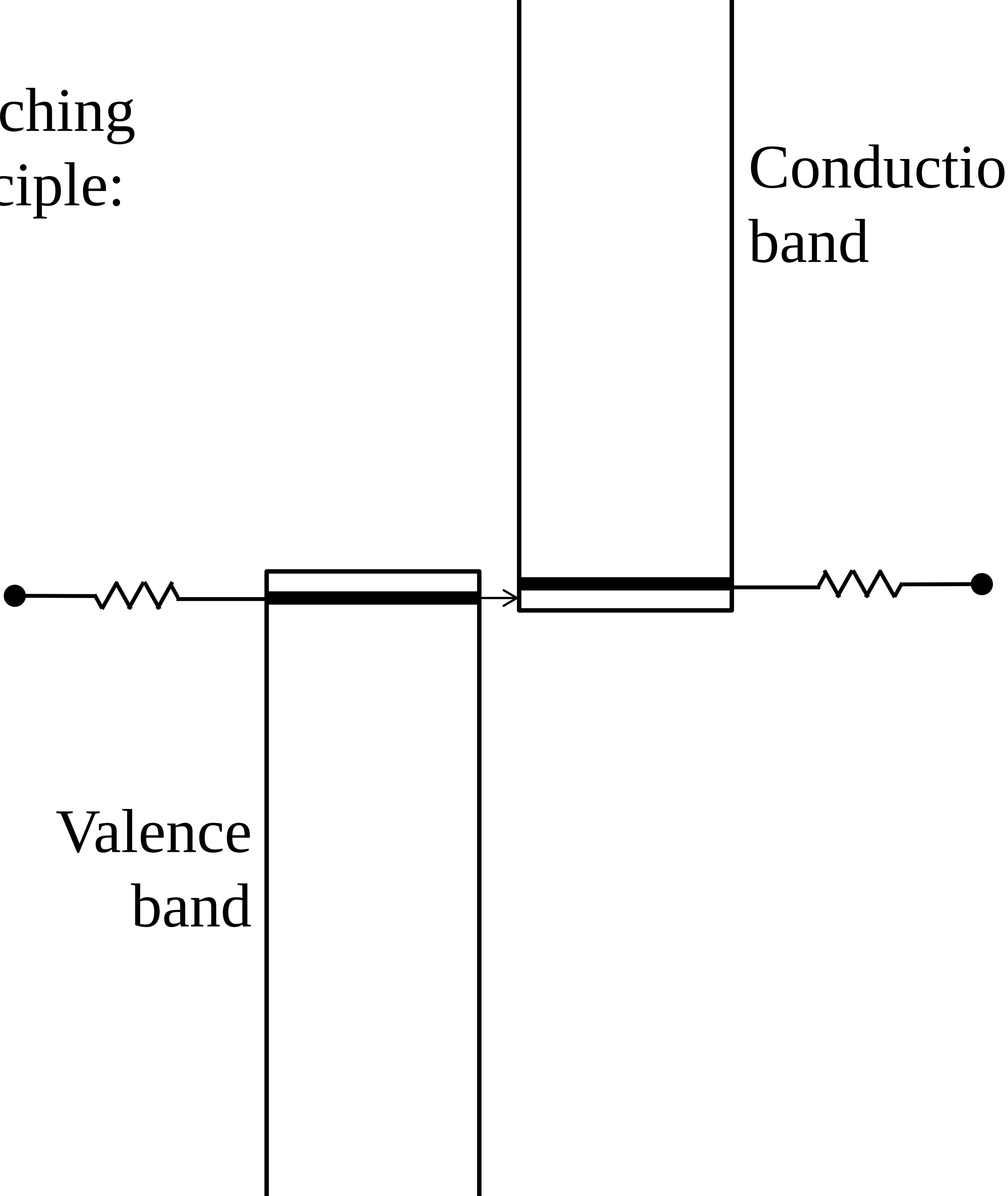
Switching Principle:



Conduction band

Valence band

Switching Principle:

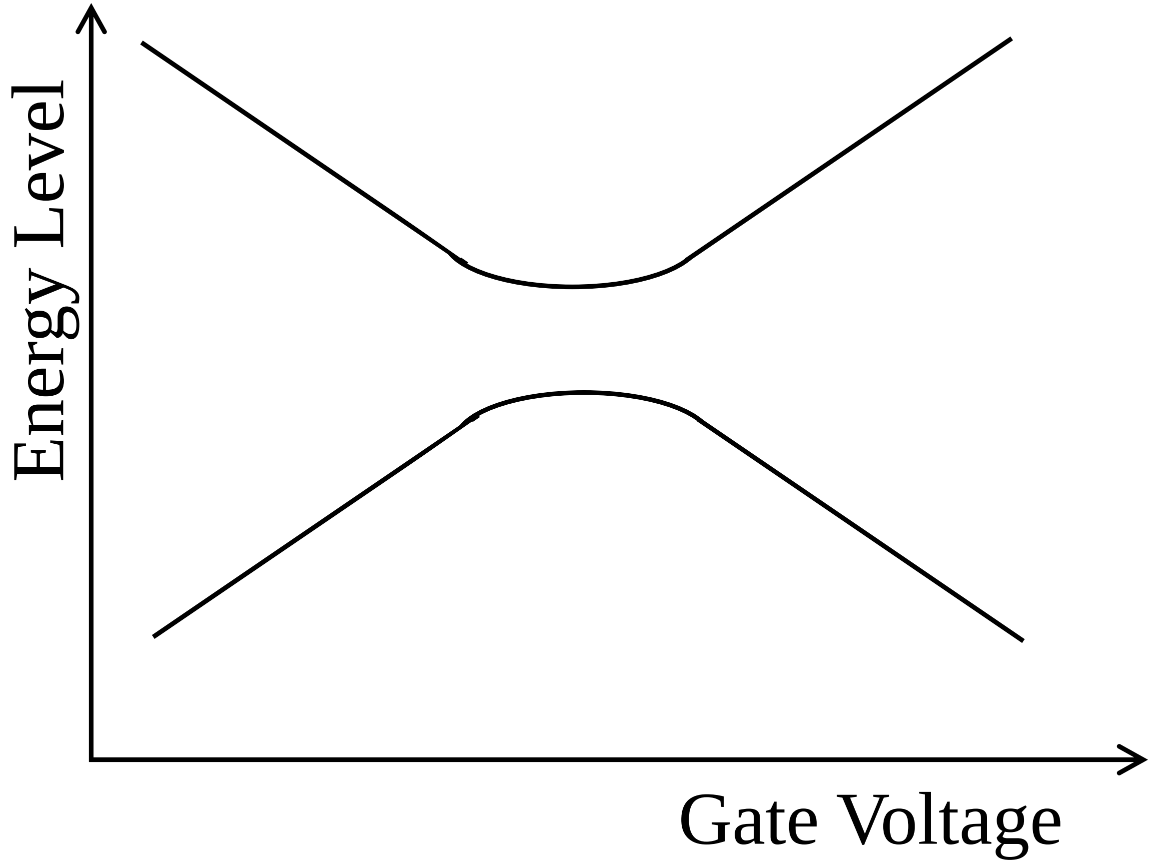


Conduction band

Valence band

What could go wrong?

1. quantum-mechanical level repulsion:



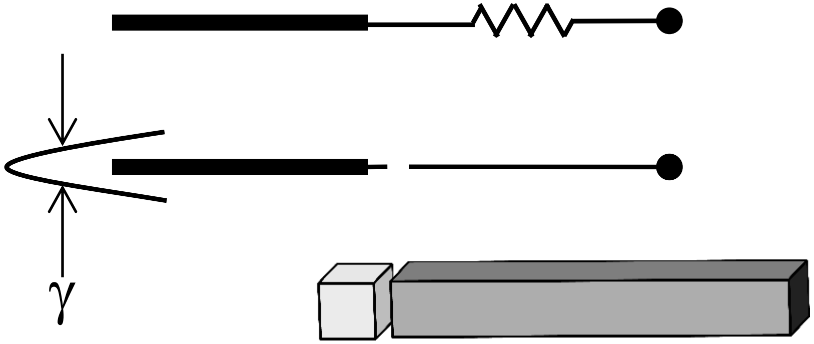
levels never line up!

What could go wrong?

2. The levels broaden due to the contacts:

conflicting requirements:

a. low contact resistance
b. sharp level



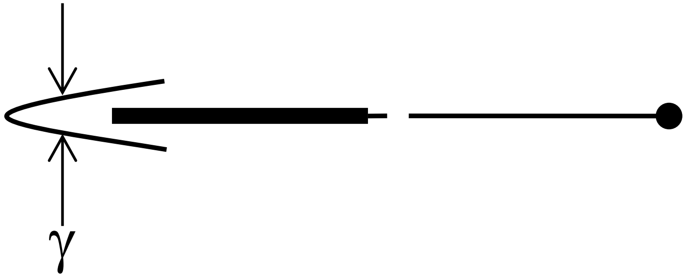
$$\text{contact conductance} = \frac{2q^2}{h} \times \frac{E_Z}{4k_b T} \times \mathcal{T}_{\text{contact}}$$

$$\text{linewidth}\ \ \gamma = (2/\pi) \times E_Z \times \mathcal{T}_{\text{contact}}$$

What could go wrong?

2. The levels broaden due to the contacts:

A compromise must be accepted:



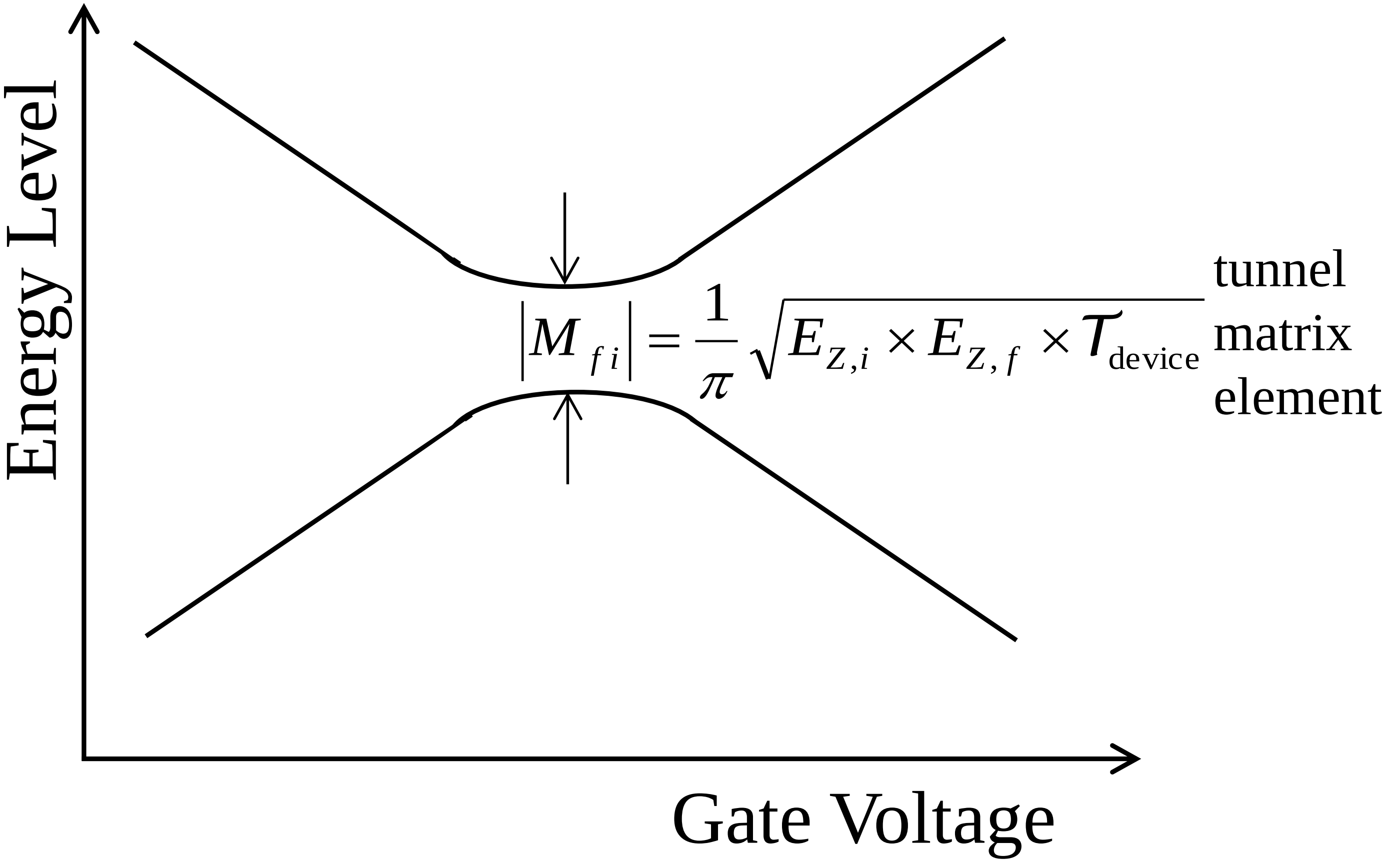
contact conductance

$$G = \frac{2q^2}{h} \times \frac{\pi}{8} \times \frac{\gamma}{k_b T}$$

Conductance quantum

Penalty for steep response

1. Solve quantum-mechanical level repulsion problem:

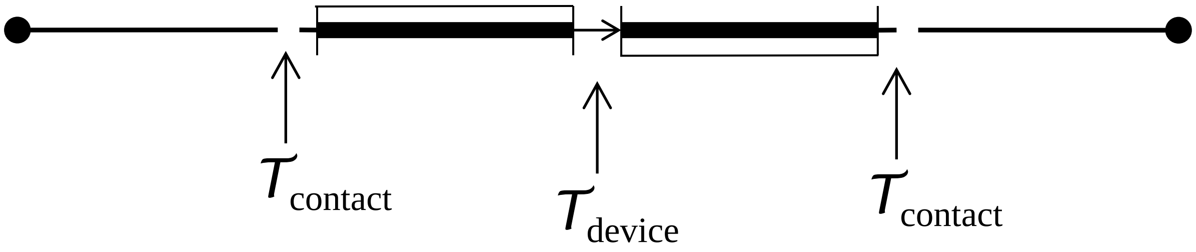


$$\left|M_{fi}\right| = \frac{1}{\pi}\sqrt{E_{Z,i} \times E_{Z,f} \times \mathcal{T}_{\mathrm{device}}}$$

tunnel
matrix
element

Ensure that contact broadening $\gamma > \left|M_{fi}\right| = \frac{1}{\pi}\sqrt{E_{Z,i} \times E_{Z,f} \times \mathcal{T}_{\mathrm{device}}}$

1. Solve quantum-mechanical level repulsion problem:



Requirement:
contact tunnel transmission is better than device tunnel transmission:

$$T_{\text{contact}} > T_{\text{device}}$$

The device tunneling probablity
should neither be to big nor too small!

What else could go wrong?

3. The contact broadening is bad enough,

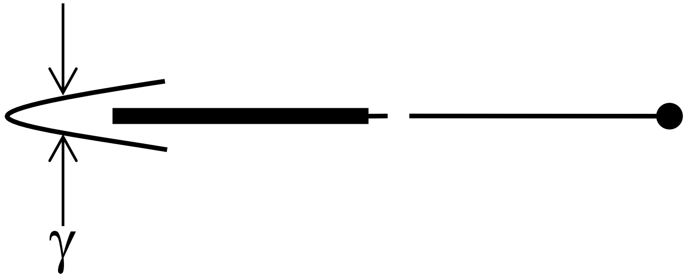
the also levels broaden due to the phonons

and due to Coulomb Blockade

and they possibly develop side-bands

also called: band tails

also called: phonon assisted tunneling



It is embarrassing to the scientific world that we know so little about this.

Both: theory is weak, and

experimental data are almost non-existent.

This science has to be a major goal of the Center

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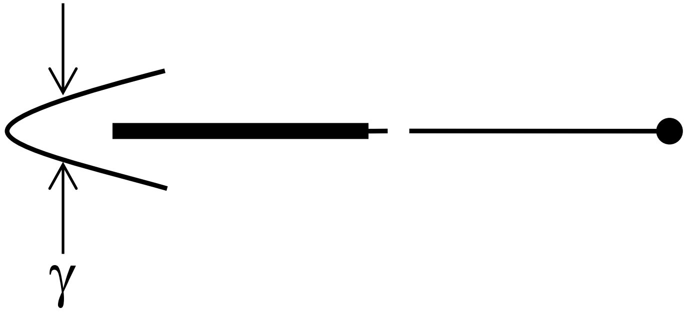

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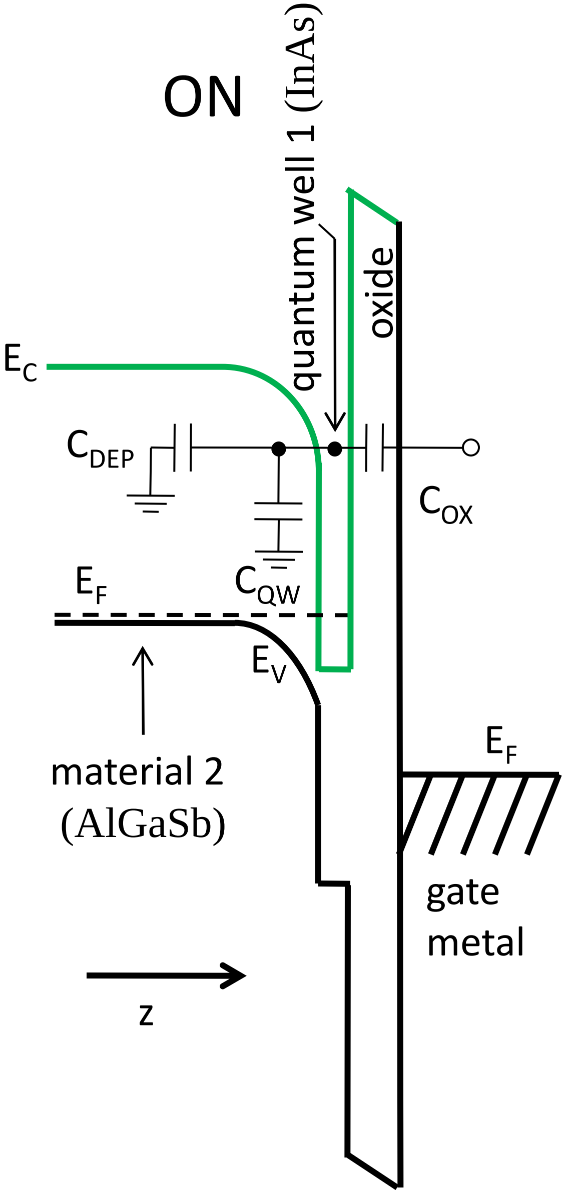
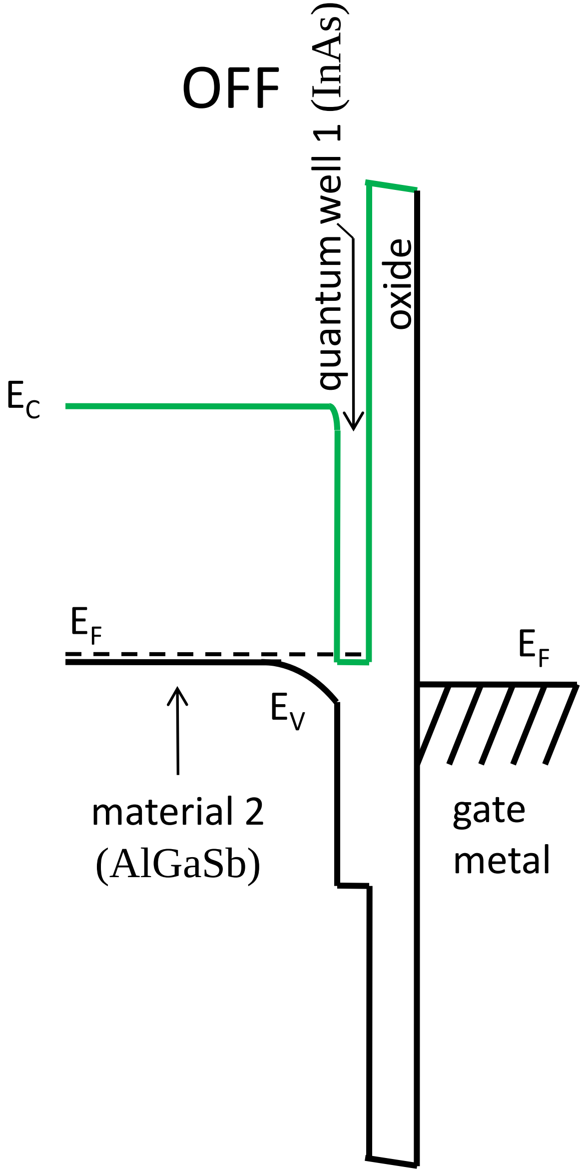
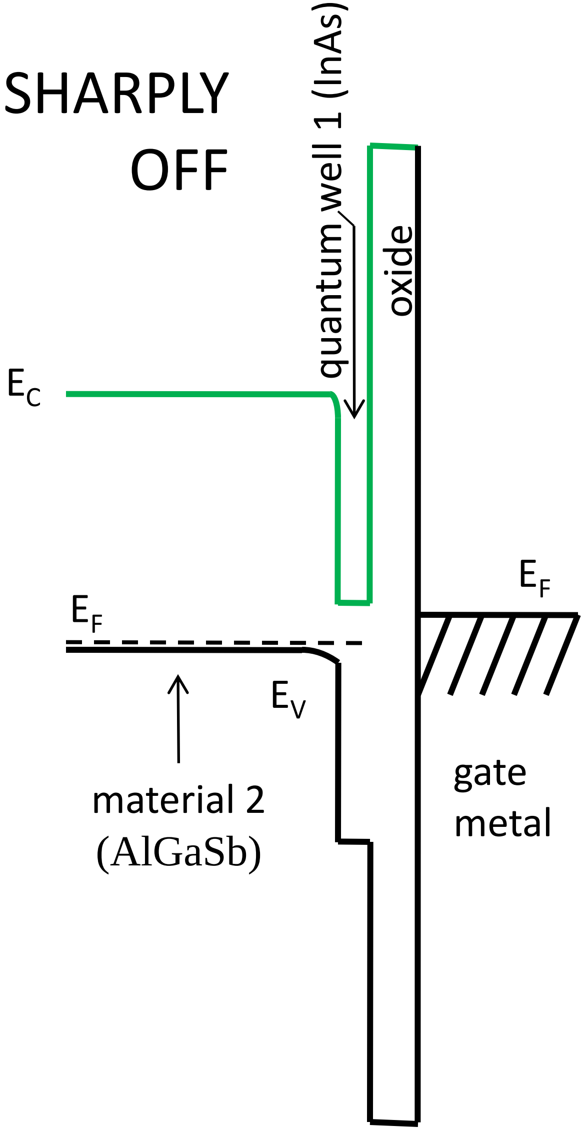


ON

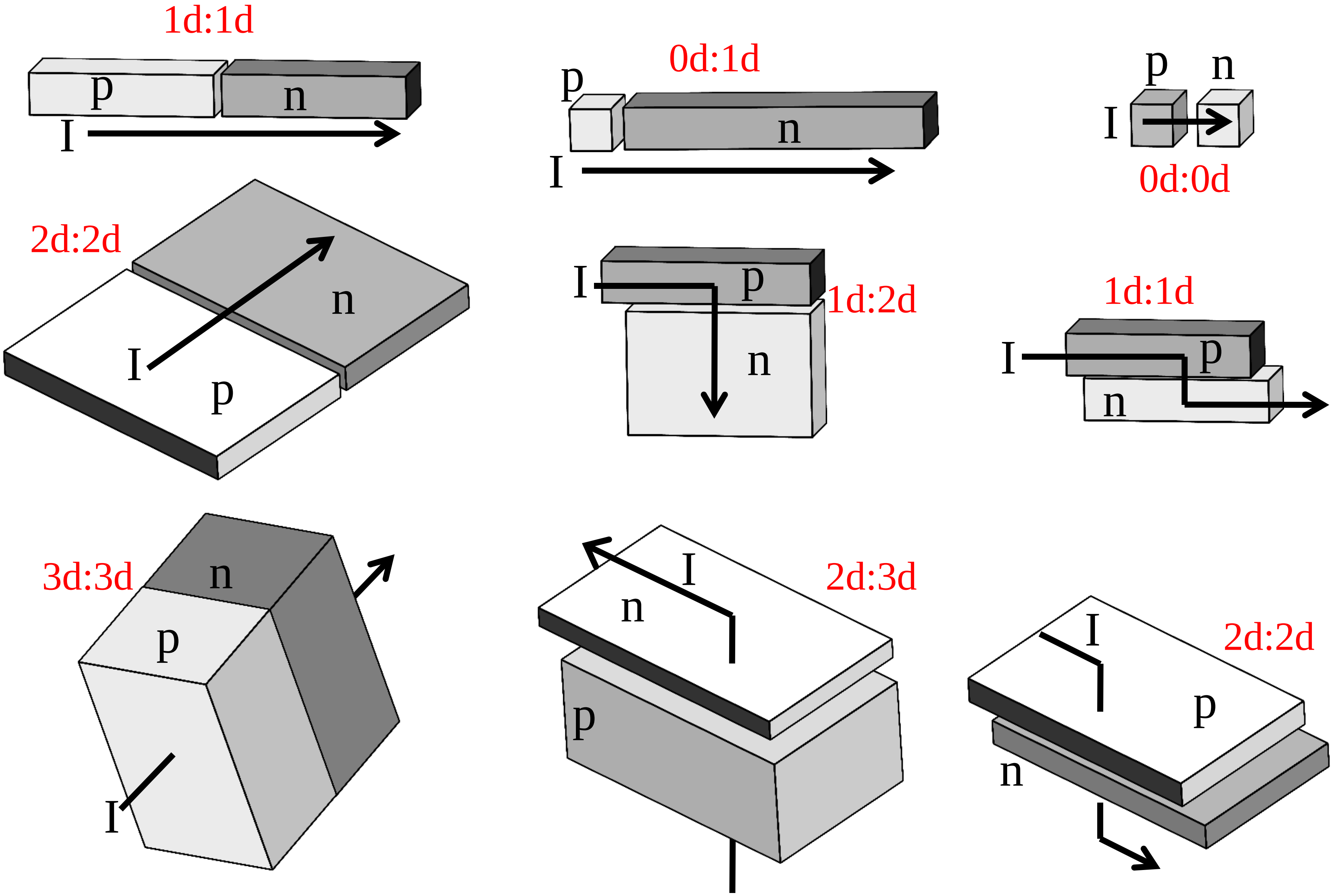


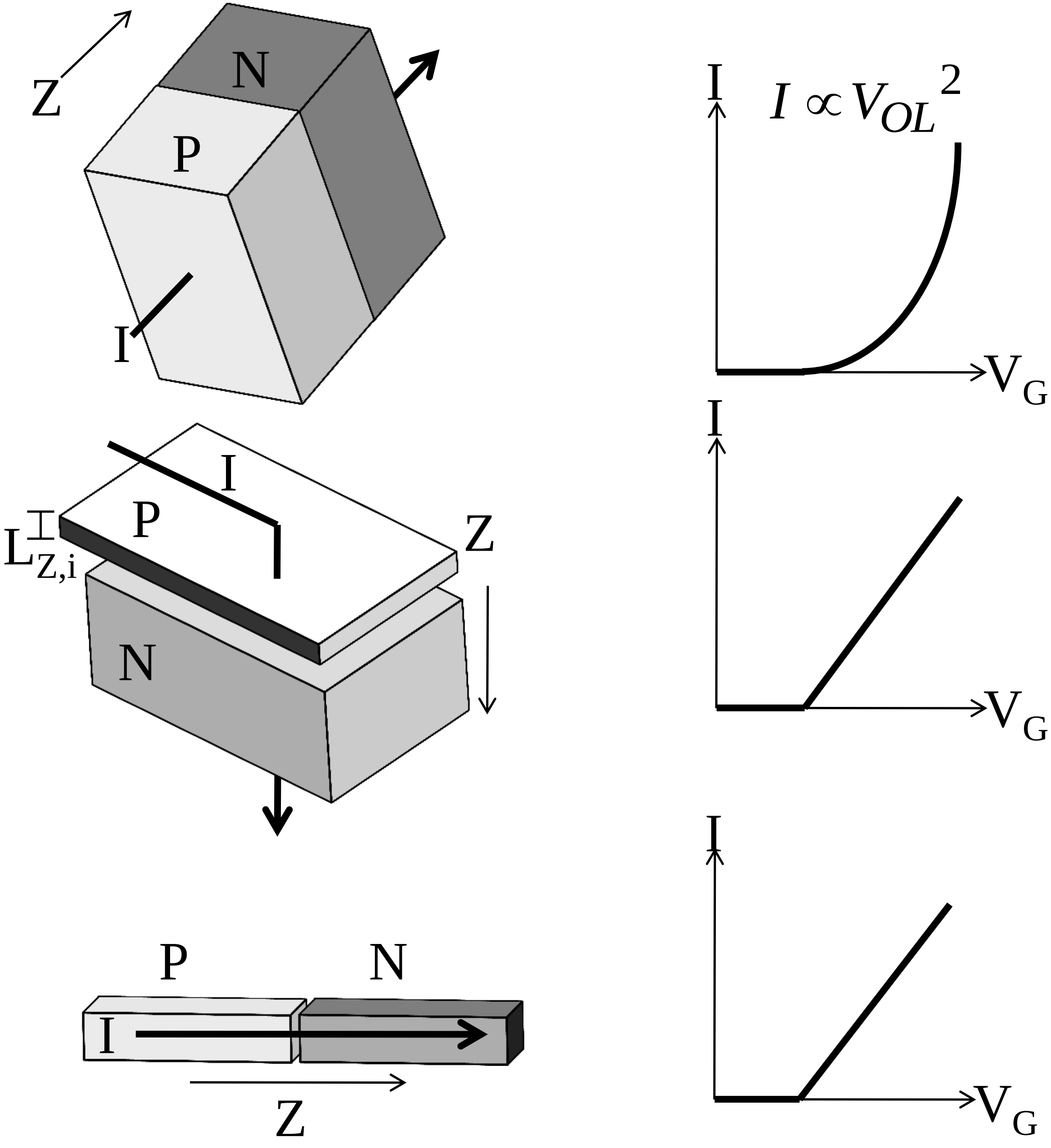
OFF

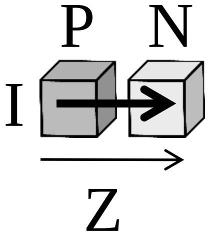


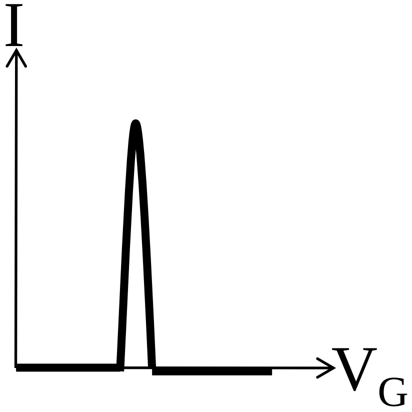
SHARPLY OFF

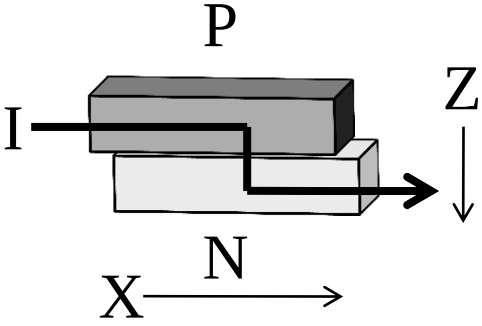
A Density of States Switch is explicitly affected by dimensionality:

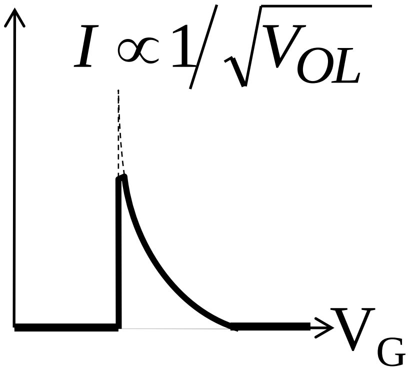


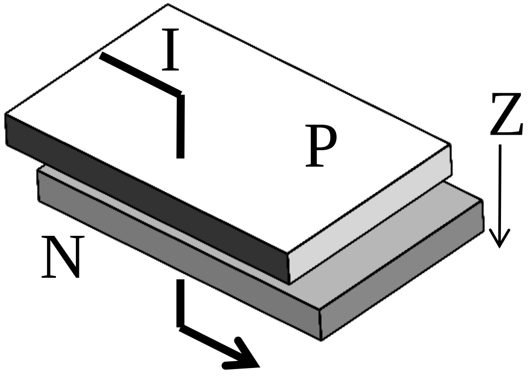

Z
N
P
I
I
$I \propto V_{OL}{}^2$
V_G
I
P
$L_{Z,i}$
Z
N
I
V_G
P
N
I
Z
I
V_G

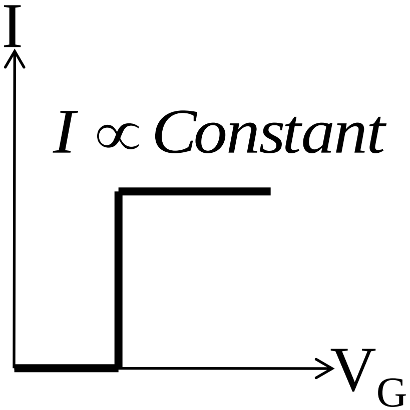

P
N
I
Z

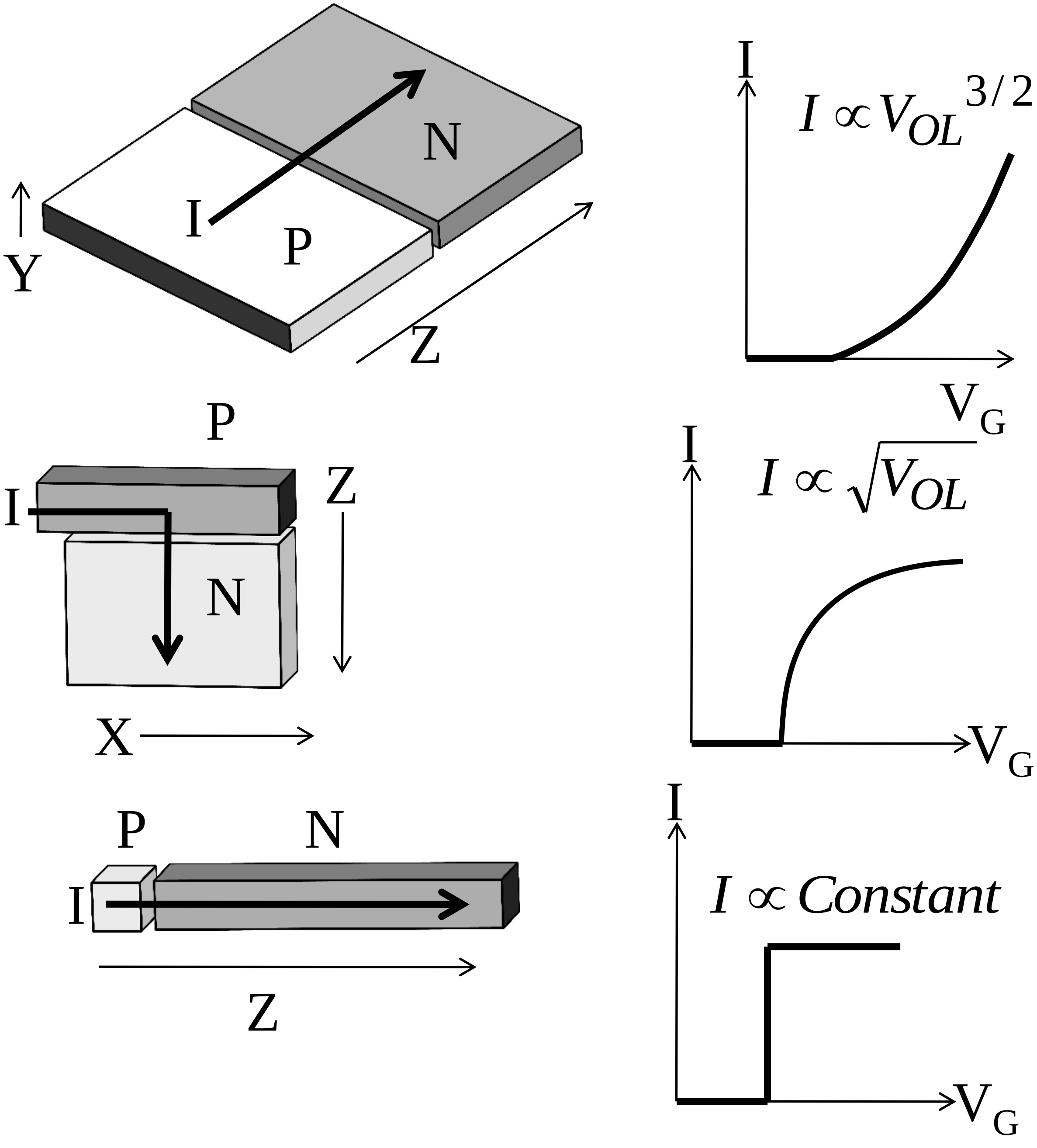

I
V_G

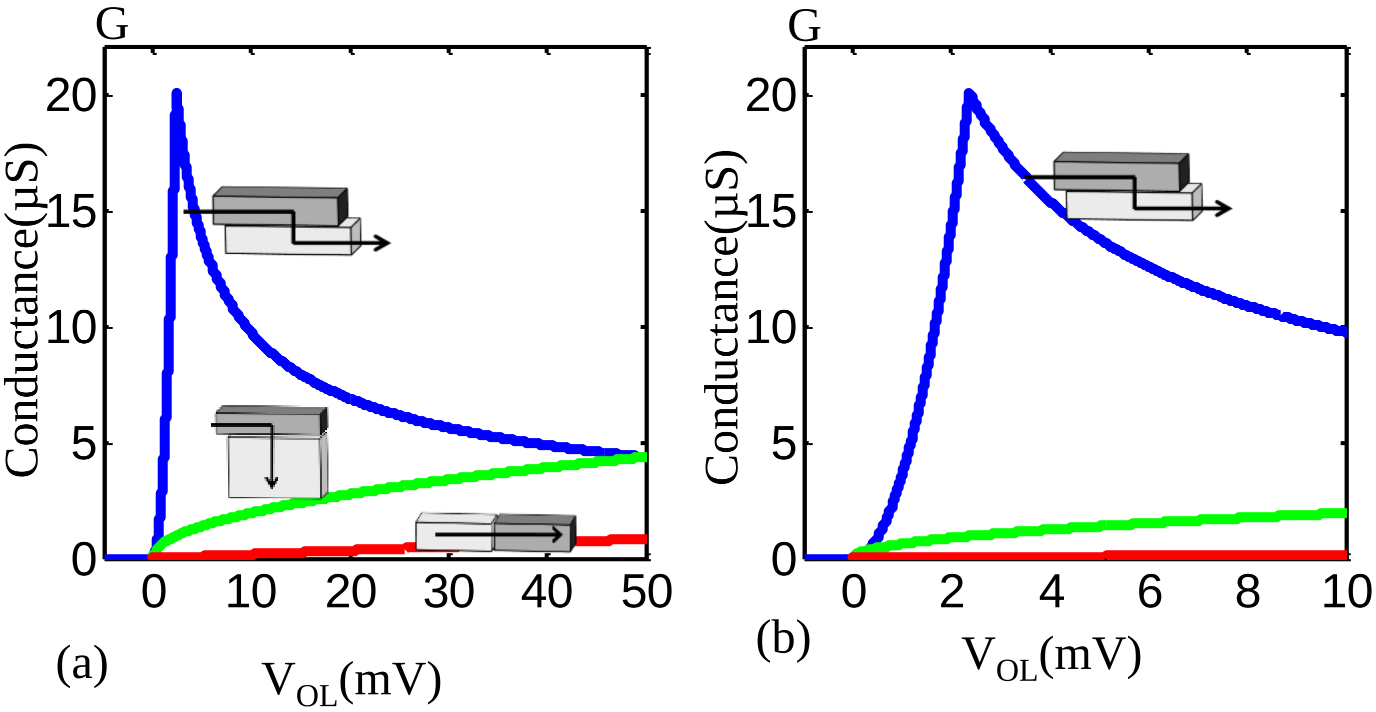

P
I
Z
N
X


$I \propto 1/\sqrt{V_{OL}}$
V_G


I
P
Z
N


I
$I \propto Constant$
V_G

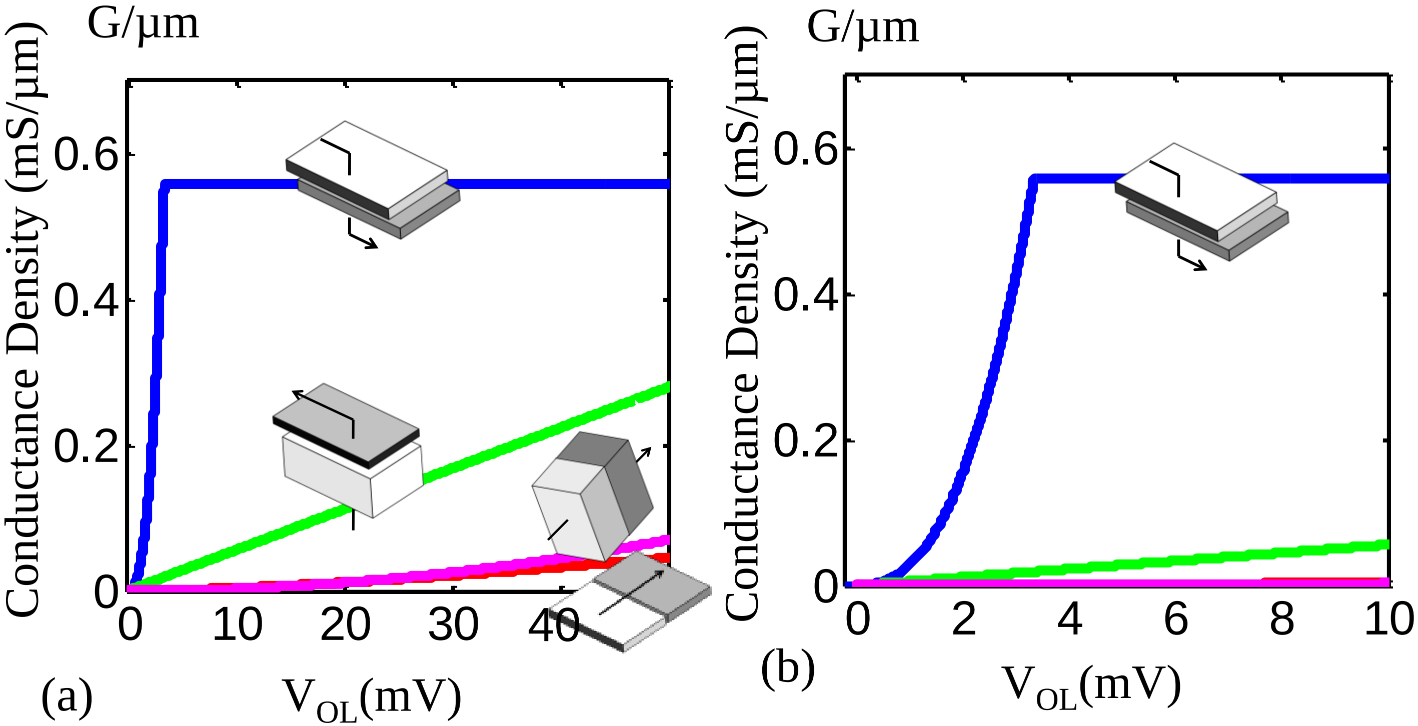

N
I
P
Y
Z
I
$I \propto V_{OL}^{3/2}$
V_G
P
Z
I
N
X
I
$I \propto \sqrt{V_{OL}}$
V_G
P
N
I
Z
I
$I \propto Constant$
V_G



γ=2.34 meV
E_Z=50 meV

T_{device}=2.16%
L_X=32 nm
L_Z=8.672 nm

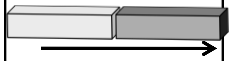
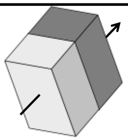
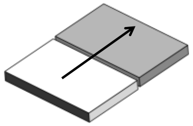
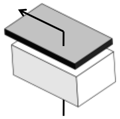
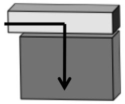
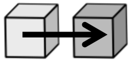
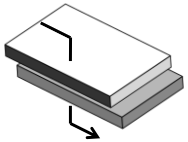
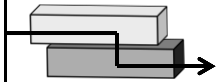
m*=0.1



γ=2.34 meV
E_Z=50 meV

$\mathcal{T}_{device}$=2.16%
L_X=32 nm
L_Z=8.672 nm

m^*=0.1

Case	**Picture**	**Current**	**Conductance, G**	**Maximum G for pert. theory to be valid**	**Maximum G for end contacts** $\gamma = (2/\pi)E_X$
1d-1d		$\frac{2q^2}{h} \times V_{OL} \times \mathcal{T}_{device}$	$\frac{2q^2}{h} \times V_{OL} \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
3d-3d		$\frac{Am^*}{4\pi\hbar^2} \times \frac{qV_{OL}}{2} \times \frac{2q^2}{h} V_{OL} \times \mathcal{T}_{device}$	$\frac{Am^*}{4\pi\hbar^2} \times \frac{qV_{OL}}{2} \times \frac{2q^2}{h} V_{OL} \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
2d-2d$_{edge}$		$\frac{2L_X\sqrt{qm^*V_{OL}}}{3\pi\hbar} \times \frac{2q^2}{h} \times V_{OL} \times \mathcal{T}_{device}$	$\frac{2L_X\sqrt{qm^*V_{OL}}}{3\pi\hbar} \times \frac{2q^2}{h} \times V_{OL} \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
0d-1d		$\frac{2q}{h} \times E_Z \times \mathcal{T}_{device}$	$\frac{2q}{h} \times E_Z \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
2d-3d		$\frac{Am}{2\pi\hbar^2} \times \frac{qV_{OL}}{2} \times \frac{4q}{h} \times E_Z \times \mathcal{T}_{device}$	$\frac{Am}{2\pi\hbar^2} \times \frac{qV_{OL}}{2} \times \frac{4q}{h} \times E_Z \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
1d-2d		$\frac{L_X}{\pi\hbar} \times \sqrt{qm^*V_{OL}} \times \frac{4q}{h} \times E_Z \times \mathcal{T}_{device}$	$\frac{L_X}{\pi\hbar} \times \sqrt{qm^*V_{OL}} \times \frac{4q}{h} \times E_Z \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	N/A	N/A
0d-0d		$\frac{4q}{\hbar} E_{Z,i} \times \frac{\mathcal{T}_{device}}{\mathcal{T}_{contact}}$	$\frac{4q}{\hbar} E_{Z,i} \times \frac{\mathcal{T}_{device}}{\mathcal{T}_{contact}} \times \frac{q}{4k_bT}$	$\frac{2q^2}{h} \times \pi^2 \times \frac{\gamma}{k_bT}$	$\frac{2q^2}{h} \times \pi^2 \times \frac{\gamma}{k_bT}$
2d-2d$_{face}$		$\frac{qmA}{\pi^2\hbar^3} \times E_{Z,i} \times E_{Z,f} \times \mathcal{T}_{device}$	$\frac{qmA}{\pi^2\hbar^3} \times E_{Z,i} \times E_{Z,f} \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	$\frac{2q^2}{h} \times \frac{\pi^3}{2} \times \gamma^2 \times \frac{1}{4k_bT} \times \frac{2mA}{\hbar^2\pi^2}$	$\frac{2q^2}{h} \times \frac{\pi^2}{4} \times \frac{W}{L_X} \times \frac{\gamma}{k_bT}$
1d-1d$_{edge}$		$2\frac{Lq}{\pi^2\hbar^2} E_{Z,i} \times E_{Z,f} \times \sqrt{\frac{m}{qV_{OL}}} \times \mathcal{T}_{device}$	$2\frac{Lq}{\pi^2\hbar^2} E_{Z,i} \times E_{Z,f} \times \sqrt{\frac{m}{qV_{OL}}} \times \mathcal{T}_{device} \times \frac{q}{4k_bT}$	$\frac{2q^2}{h} \times \sqrt{2}\pi^2 \times \gamma^{3/2} \times \frac{1}{4k_bT} \times \sqrt{\frac{2mL^2}{\pi^2\hbar^2}}$	$\frac{2q^2}{h} \times \frac{2\pi^{3/2}}{4} \times \frac{\gamma}{k_bT}$

The Milli-Volt Switch
Key Scientific Questions:

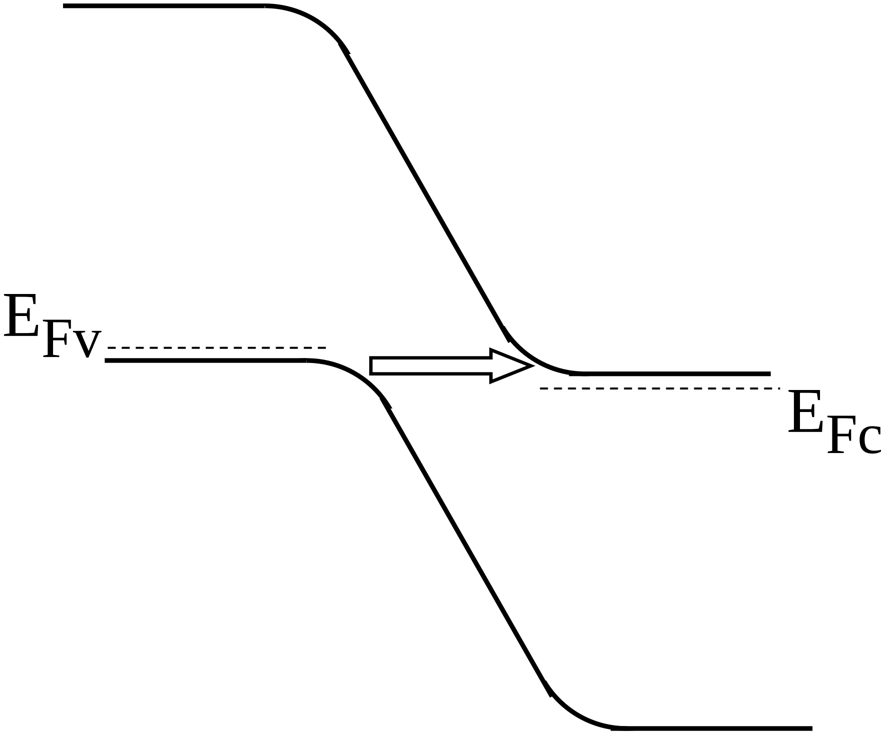
- Fundamental band edge abruptness is very poorly understood.

- New examples of Type III Energy band offsets need to be discovered.

- Do we need to concentrate on 2d/2d pn junctions?

- Will that guarantee reproducible thresholds?

The Backward Diode as a Switch:



The Backward Diode:

These have been routinely made in Ge homo-junctions, since the 1960's.