EE331: Day I: Syllabus, Overview, Modeling Time

Syllabus notes:

- Labs: 35%
- HW: 10%
- Quizes: 5%
- Exams: 60%
  - MT (Best) 20%
  - MT (Worst) 10%
  - Final: 30%

Overview:

- Physics of Conduction
- Quantum Exclusion (IE Band Gap)
- Semiconductors
- Doping
- Junctions

- Diodes
- Modeling & Context
- Linear/Nonlinear Combinations
- Designs

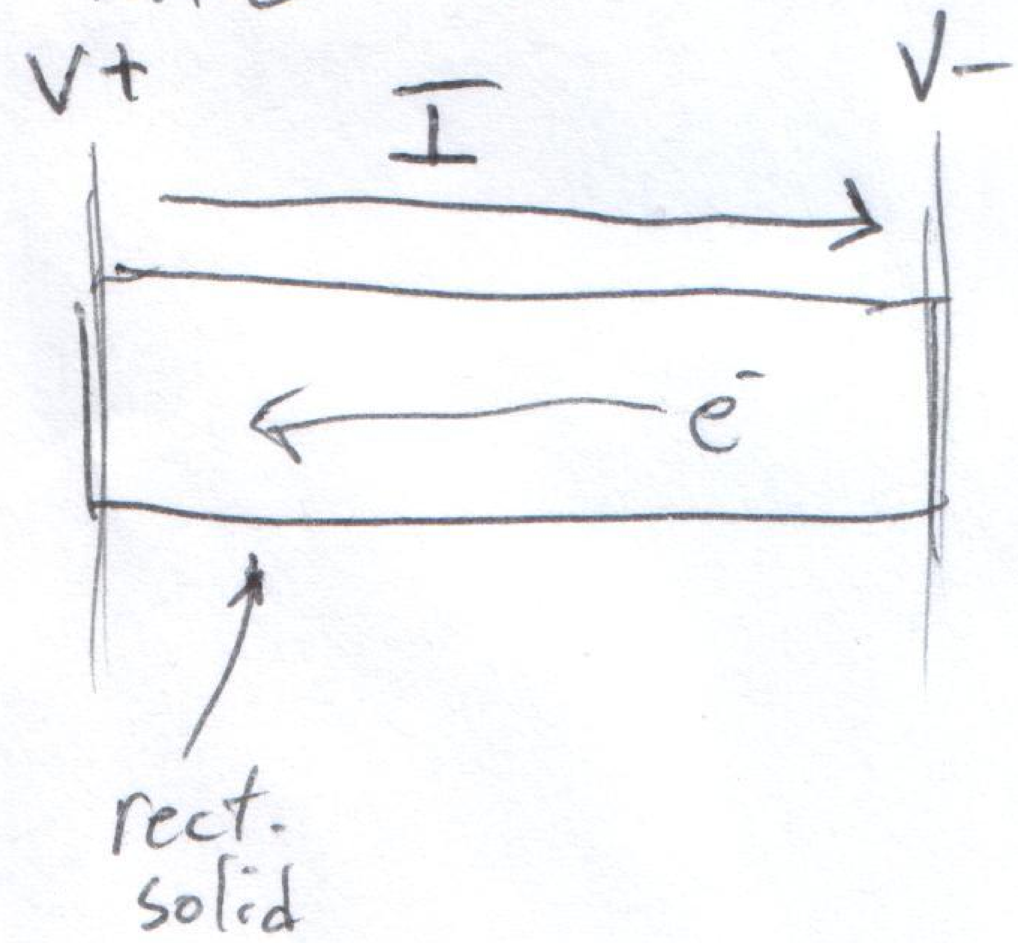
- FETs
- Modeling & Context
- Designs

- Logic Design

Labs

- Data Aq./LabView
- Diode Behavior
- Diode Circuit Applications
- Transistor Behavior
- Trancistor Circuits
- More Transistor Circuits
- Design Project

So. Let's take a look at resistors.



- motion not ballistic
- leads to ohms law

$$V = IR, \quad R = \sigma \cdot \frac{L}{W \cdot H}$$

Physics of Conduction:

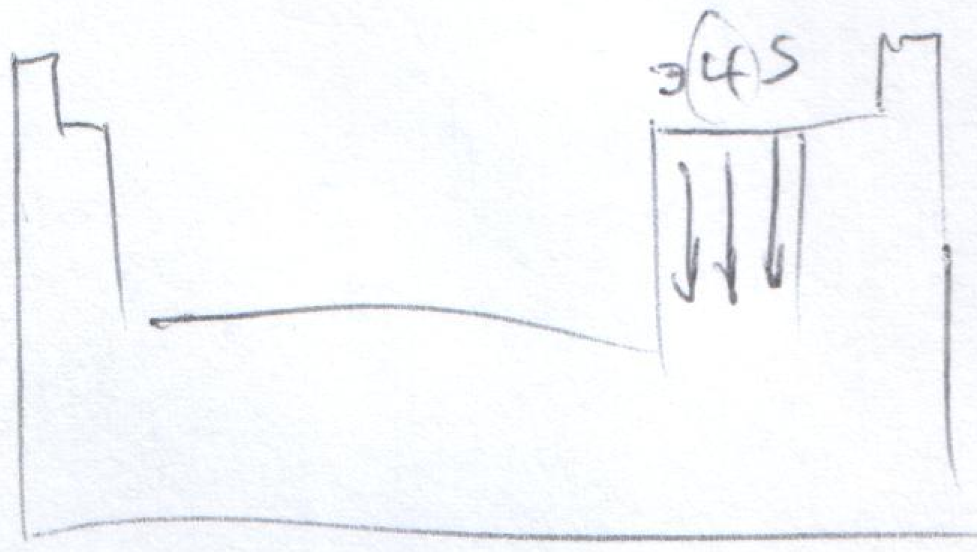
In Vacuum:
- throw an electron
- electron goes as $\vec{F} = m\vec{a}$

In nonconductor:
- no available "waves" for electron to join
- "mobility" is low

in metals:
- many orbitals
- electrons very loosely shared
- tiny differences in momentum between "stuck" and "free"

Today:

Resistors, made of semiconductors!



3	4	5	
B	C	N	O
Al	Si	P	
Ga	Ge	As	
In	Sn	Sb	
Tl	Pb	Bi	

Key semicond.

But of course silicon is the big one.

4 valence electrons connect neighbors in "diamond configured silicon"

2 — Si — 2, 2 above, 2 below

not going anywhere

At abs. zero, all vacancies are filled so nothing moves. given any thermal energy, a few will get loose.

Semiconductor Carrier Density as a function of temperature:

$$n_i^2 = BT^3 e^{-\frac{E_G}{kT}}$$

units: cm^{-6}

E_G: Energy Gap (1.12eV in silicon)

B: material param. $1.08 \times 10^{31}\ K^3 \cdot cm^{-6}$ in silicon

T: temp, K

k: Boltzmann's constant 8.62×10^{-5} eV/K

T: temp, K

n_i: #carriers / cm^3

Manipulating p & n: Donors & Acceptors

"Acceptors" 3^+
- B
- Al
- Ga
- In

"Donors" $^-$
- N
- P
- As
- Sb

Donors & Acceptors are still electrically neutral but make the lattice adjust to be tilted towards more holes or more (free) electrons.

(on their own, these elements tend to form very different crystals than Si, but in mostly-silicon lattices, they fit in.)

N_D: $\cancel{\#\text{atoms}/\text{cm}^3}$

N_A: $\cancel{\#\text{atoms}/\text{cm}^3}$

To not ionize, we must have:

$$\underline{q(N_D + p - N_A - n) = 0}$$

At thermal equilibrium, we will also have:

$$\underline{pn = n_i^2}$$

Negative Doping <P, As, Sb>

Phosphorous, Arsenic, Antimony

$$N_D \gg N_A \qquad n = \frac{N_D + \sqrt{N_D^2 + 4n_i^2}}{2}, \quad p = \frac{n_i^2}{n}$$

Positive Doping <B, Al, Ga, In>

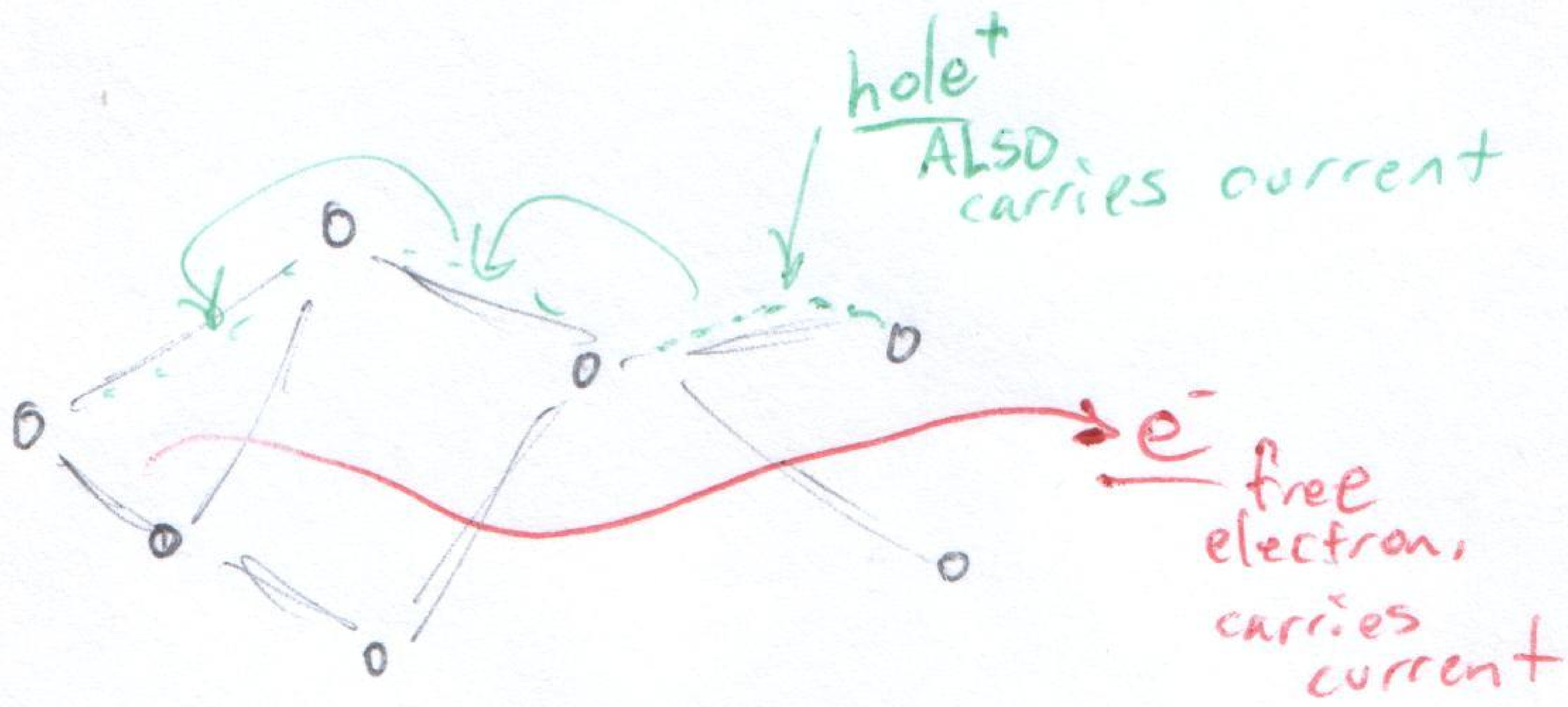
$$N_A \gg N_D \qquad p = \frac{N_A + \sqrt{N_A^2 + 4n_i^2}}{2}, \quad n = \frac{n_i^2}{p}$$

Practically:

	n-type:	p-type:
	$n \simeq N_D$	$p \simeq N_A$
	$p \simeq \frac{n_i^2}{N_D}$	$n \simeq \frac{n_i^2}{N_A}$

$n_i : \simeq 10^{10}$, silicon @ room temperature (6.73×10^{9})

Holes & Electrons



$$\underbrace{\overset{\text{holes}^+}{p} \cdot \overset{e^-}{n} = n_i^2}$$

true for all semiconductors in thermal equilibrium.

Drift Current:

"regular resistive current"

All currents are $\frac{\text{Coulomb}}{\text{second}}$ so current density is $\frac{C}{s \cdot cm^2}$ or $\frac{A}{cm^2} \rightarrow \vec{j} = Q\vec{V}$

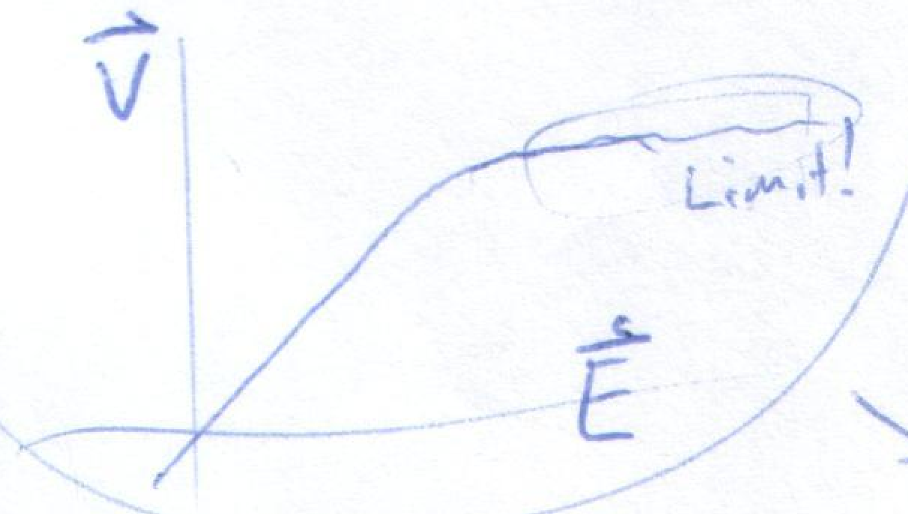
Q: charge density

$\vec{V}$: charge velocity

Charges in motion for DRIFT:

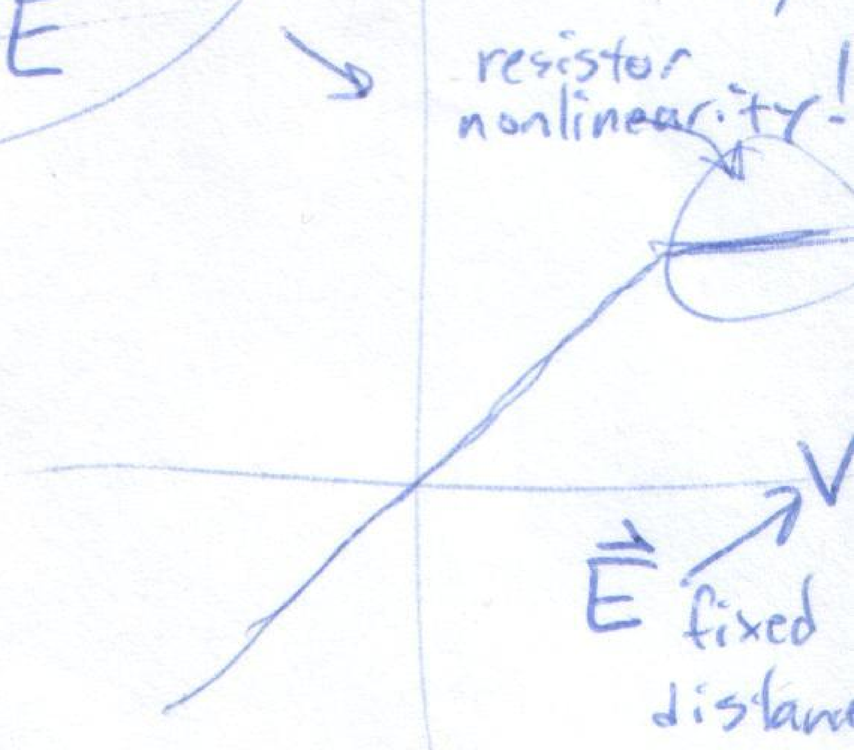
$$\vec{V}_p = \mu_p \cdot \vec{E} \quad , \quad \vec{V}_e = -\mu_e \cdot \vec{E}$$

Note: Velocity saturation limits how fast electrons will move:



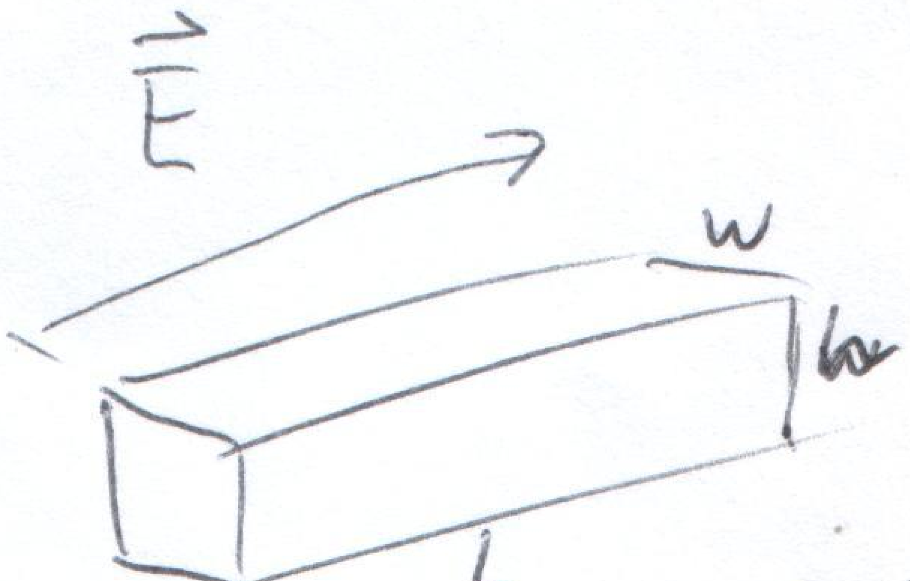
$\vec{V}_d$ fixed cross-section & charge density

$j \rightarrow I$



$$\vec{j}_{drift} = \underbrace{\overset{Q}{(-qn)}\overset{\vec{V}}{(-\mu_n \vec{E})}}_{\overleftarrow{e^-},\ \overrightarrow{i}} + \underbrace{\overset{Q}{(qp)}\overset{V}{(\mu_p E)}}_{\overrightarrow{h^+},\ \overrightarrow{i}}$$

$$j = \underbrace{q(n\mu_n + p\mu_p)}_{\sigma,\ \Omega/cm} E$$



$V = L \cdot \vec{E}$

$j = \frac{I}{\text{Area}}$ $\quad \frac{I}{h \cdot w} = \sigma \cdot V/L$

$$V = I \frac{1}{\sigma} \frac{L}{h \cdot w}$$

$\rho = \frac{1}{\sigma}$, res.

$R \longrightarrow V = I\boxed{R} \ldots$

$V \to \vec{E}\cdot D = \underbrace{\vec{J}\cdot A}_{I} \cdot R$

physics → particle density

★ R: $\vec{v}_e = -\mu_e \vec{E}$, $\vec{v}_p = \mu_p \vec{E}$

$\cancel{\vec{J} = (-qn)(\mu_n \vec{E})}$

μ: "mobility" $\dfrac{m/s}{\frac{V}{m}\vec{E}}$ AKA: $\dfrac{1}{V\cdot s}$

$\vec{J} = \underbrace{q(n\mu_n + p\mu_p)}_{\boxed{\sigma}}\vec{E}$

$\cancel{I = \frac{J}{W\cdot L}}$

$\boxed{I = j(w\cdot h)}$

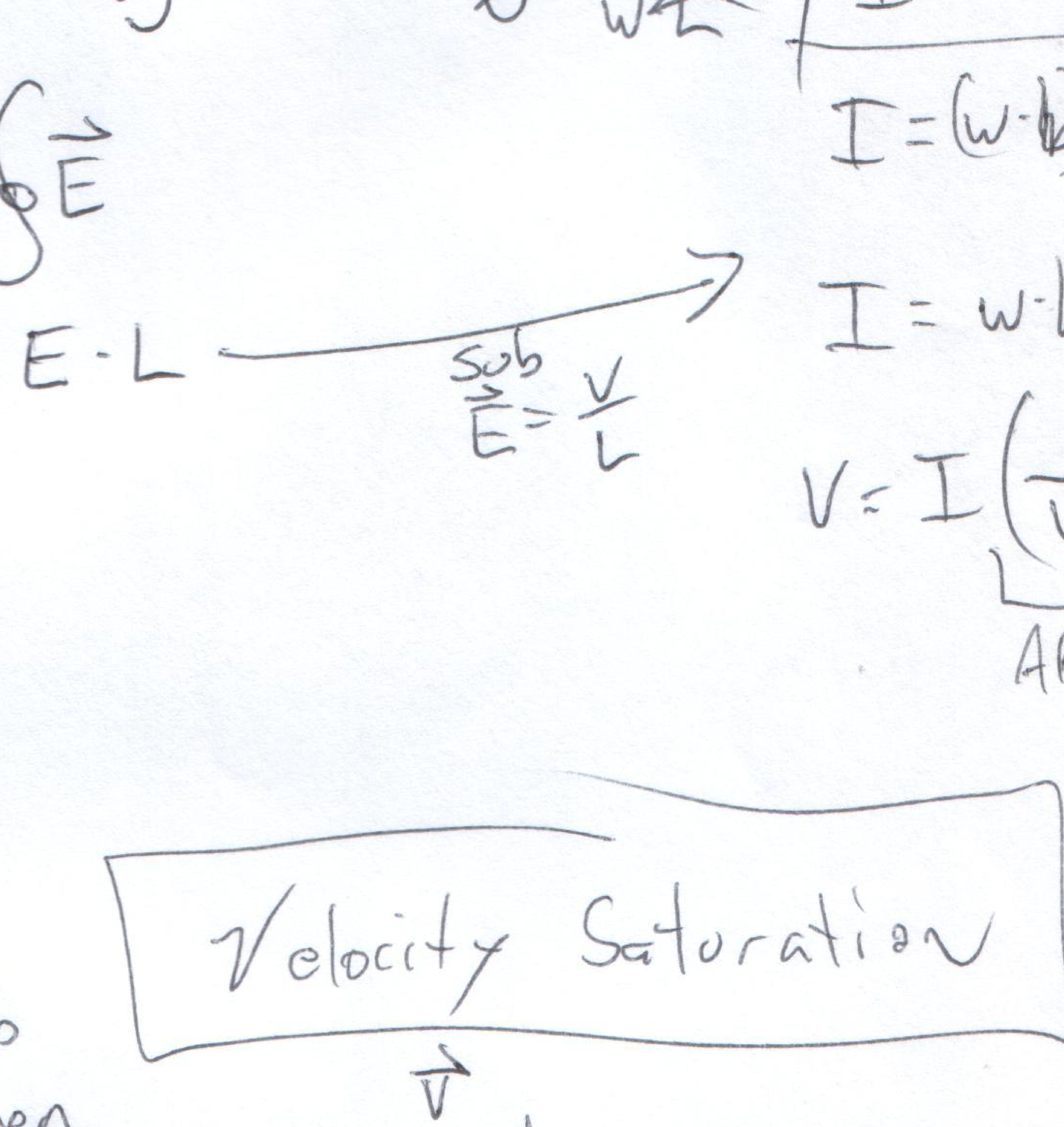
$I = (w\cdot h)\,\sigma\cdot\vec{E}$

$V \equiv \int \vec{E}$

$V = E\cdot L \xrightarrow{\text{sub } \vec{E} = \frac{V}{L}} I = w\cdot h\,\sigma\,\dfrac{V}{L}$

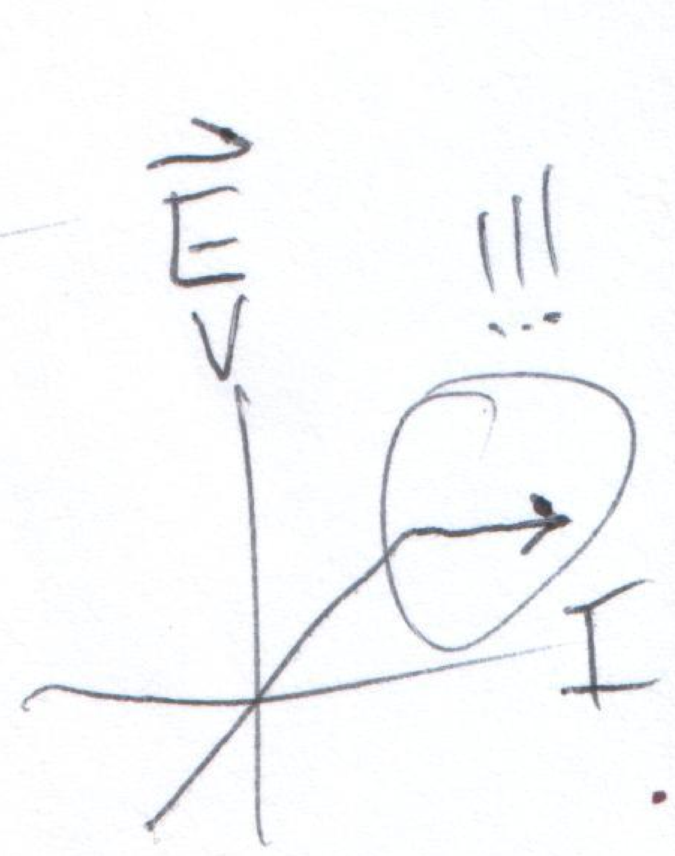
$V = I\underbrace{\left(\dfrac{L}{w\cdot h\cdot\sigma}\right)}_{\text{AKA: "a resistor"}}$

Velocity Saturation



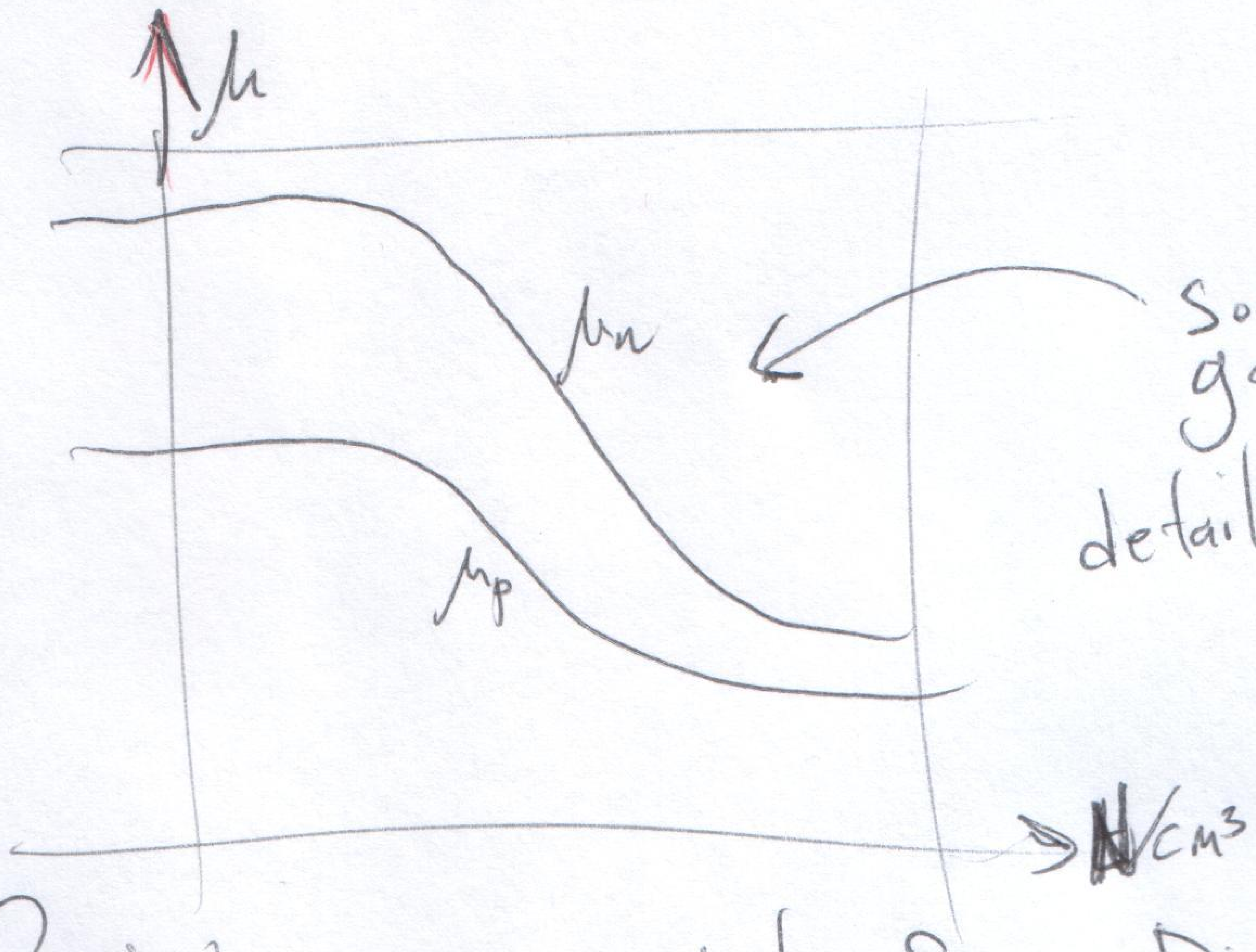
Quiz: if a light bulb runs at 60W when attached to a 120V DC source (Edisoooon) find its resistance $= 240\Omega$

You unplug and measure with a DMM. 0.01Ω. Explain.



$$\rho = \frac{1}{q(n\mu_n + p\mu_p)}$$

So we also need μ_n, μ_p



Some graph, details? look it up...

Resistance, quick & Dirty:

N type? ⟷ P type

N type:

μ_n, μ_p, look up

$n = N_D$ $\quad p = \frac{n_i^2}{n}$

$$\boxed{\rho \simeq \frac{1}{q\mu_n N_D}}$$

P type:

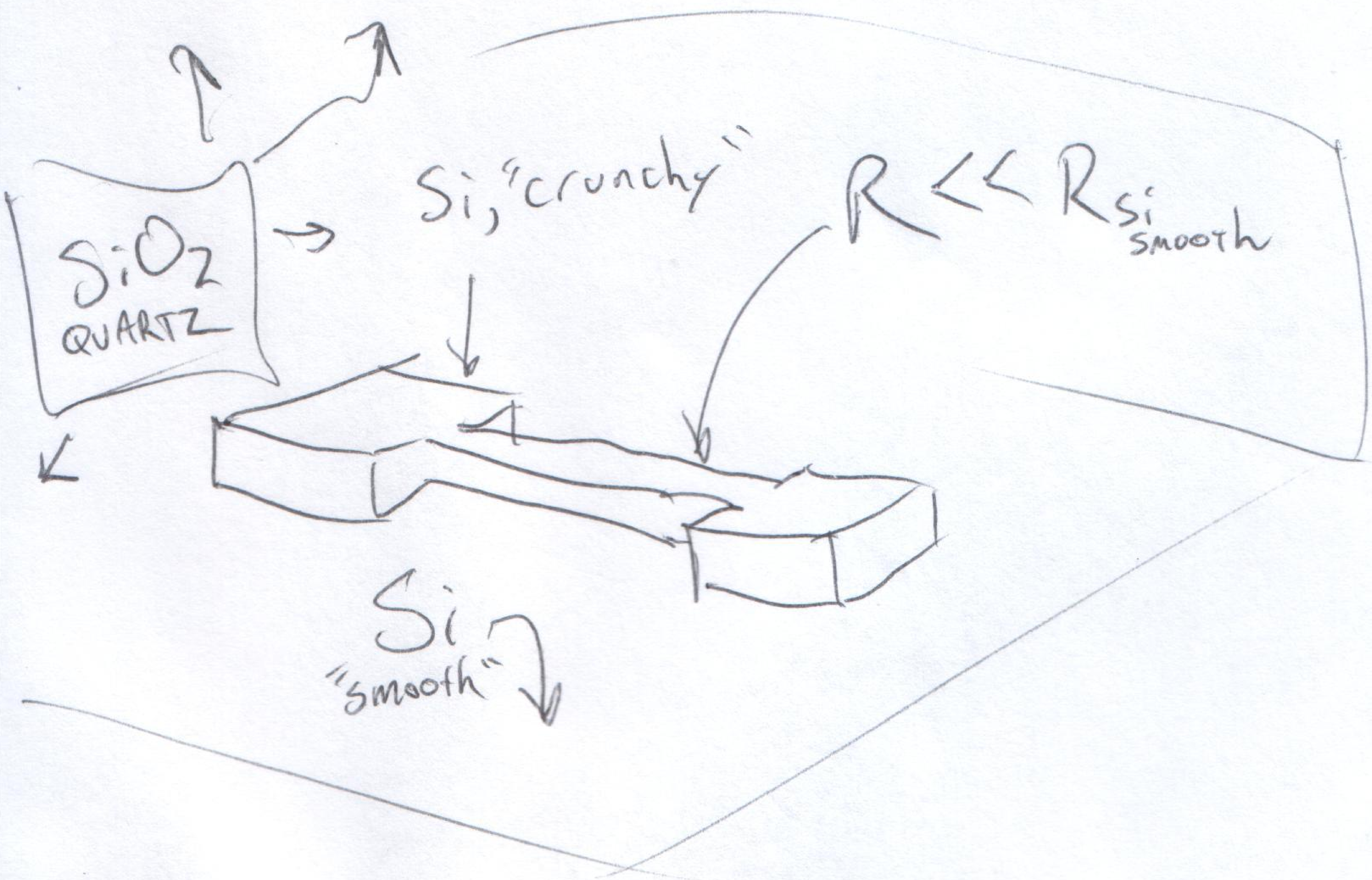
μ_n, μ_p look up

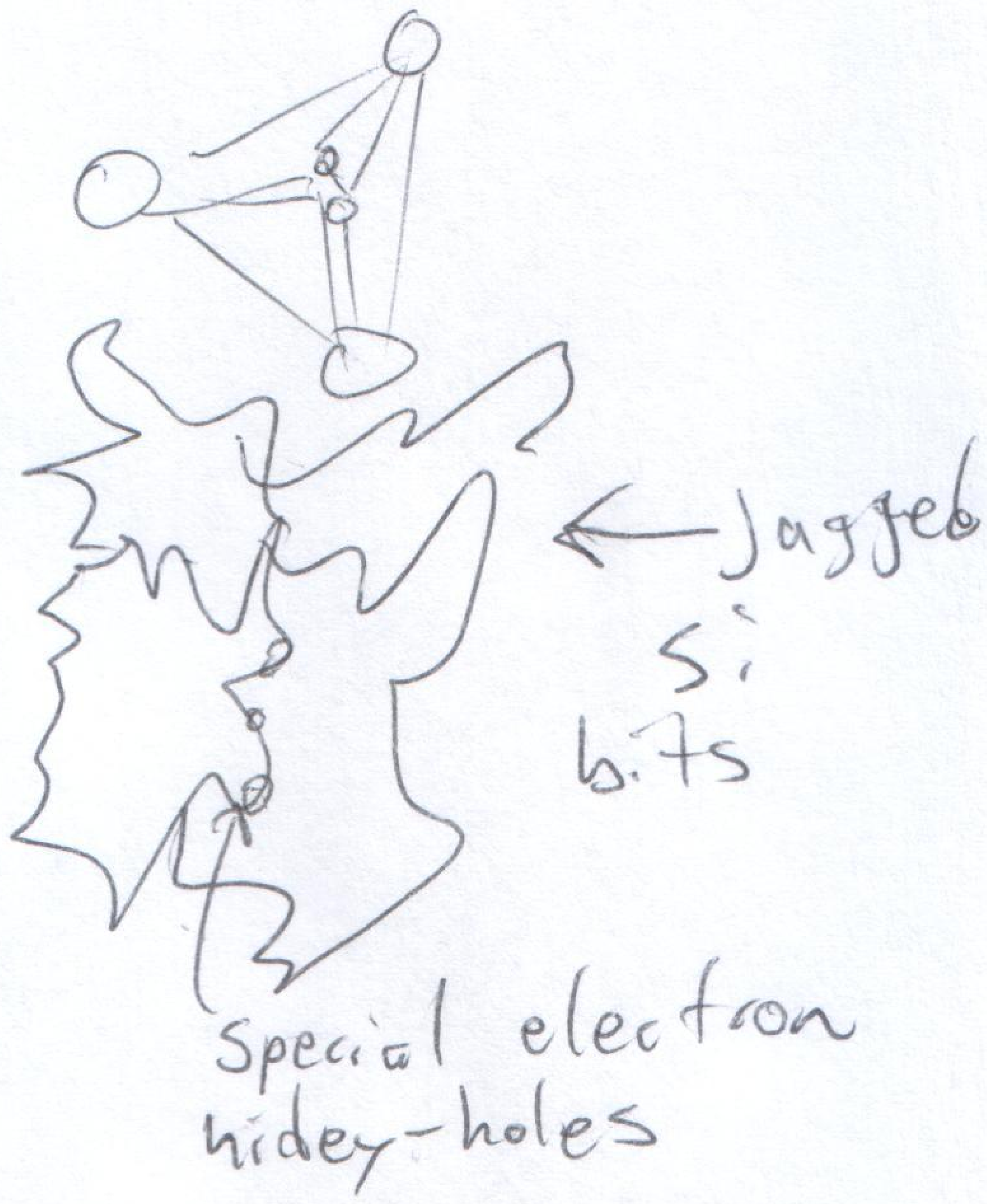
$p = N_A$ $\quad n = \frac{n_i^2}{p}$

$$\boxed{\rho \simeq \frac{1}{q\mu_p N_A}}$$

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)} \longrightarrow R = \rho \frac{L}{W \cdot H}$$

Aside: Polysilicon Resistors

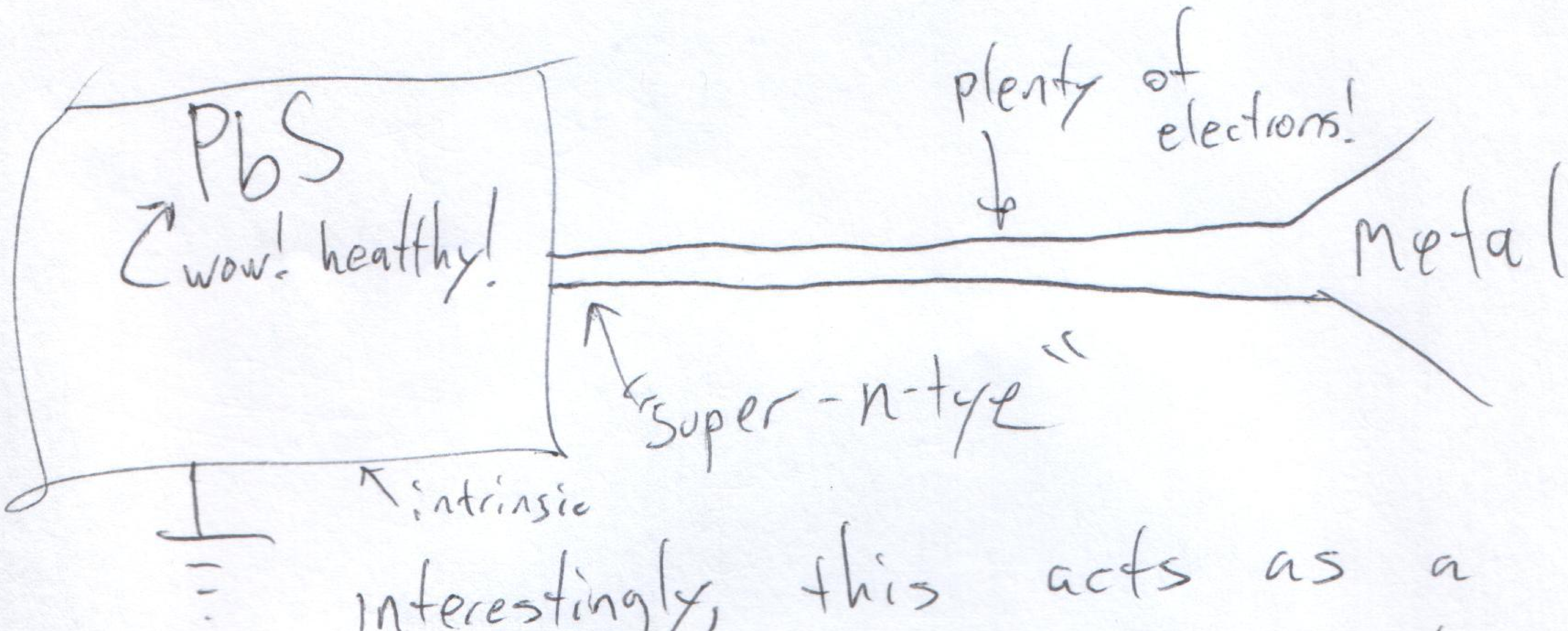




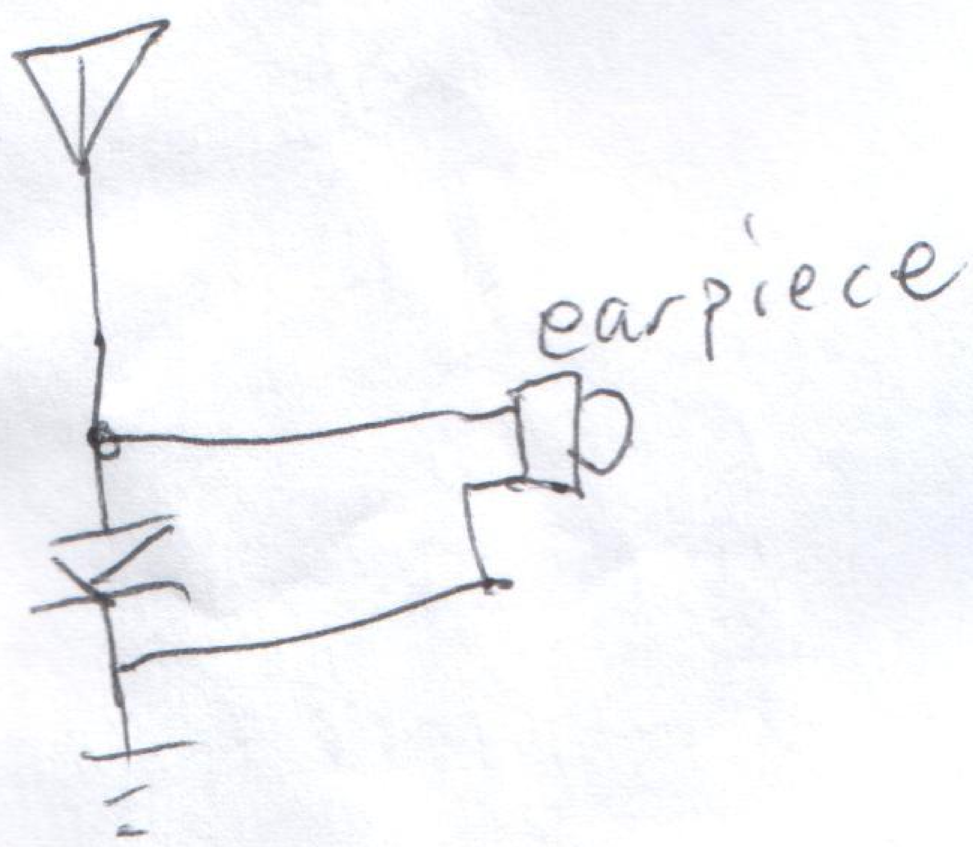
Note: 2D-Fabrication processes have been LAW for like 40+ years

And then, diodes happened.

Sidebar: the galena diode



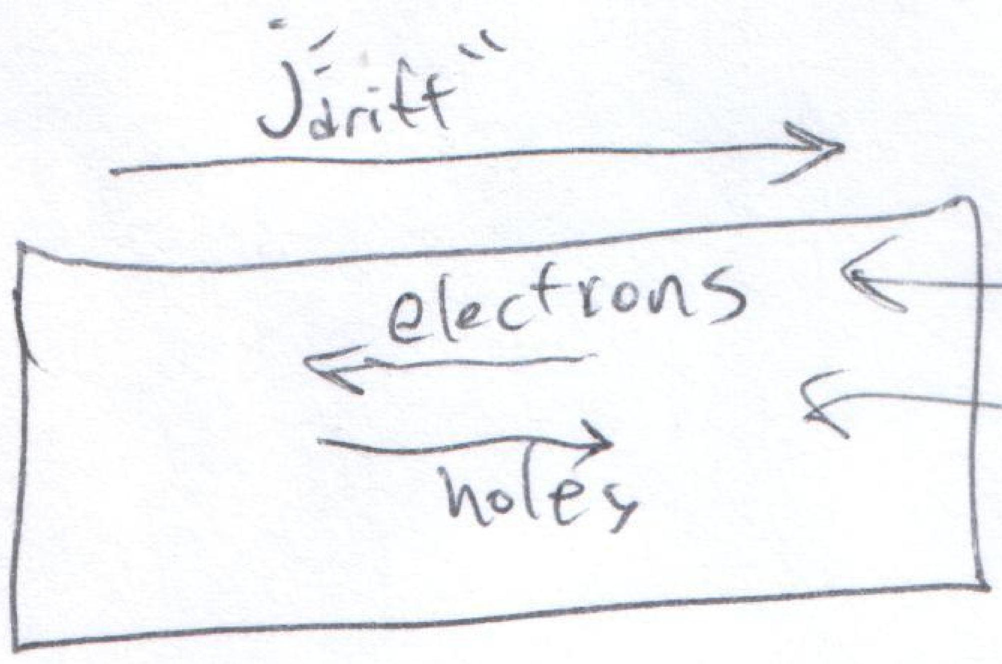
interestingly, this acts as a one way-ish circuit element.



Radio recievers can and have been built in the past by literally attaching quartz and galena to a lot of wire.

This is about as close to minecraft-punk as EE gets.

Quick review of resistance in doped semicond:



One of these probably negligible

$$j = q \cdot \# \cdot \mu \cdot E$$

e field

charge

population

mobility, speed/E trade

Resistivity:

$$\underbrace{\sigma \simeq qN_D\mu_n}_{\text{N-type}} \qquad \underbrace{\sigma \simeq qN_A\mu_p}_{\text{P-Type}}$$

Solids, semiconductors especially, are basically pain sticks for electrons/holes to "fall" through under an electric field.

$$\boxed{p \cdot n = n_i^2}$$

number of charge carriers is $\underline{p+n}$ so $p=n$ is actually the LOWEST number of carriers!

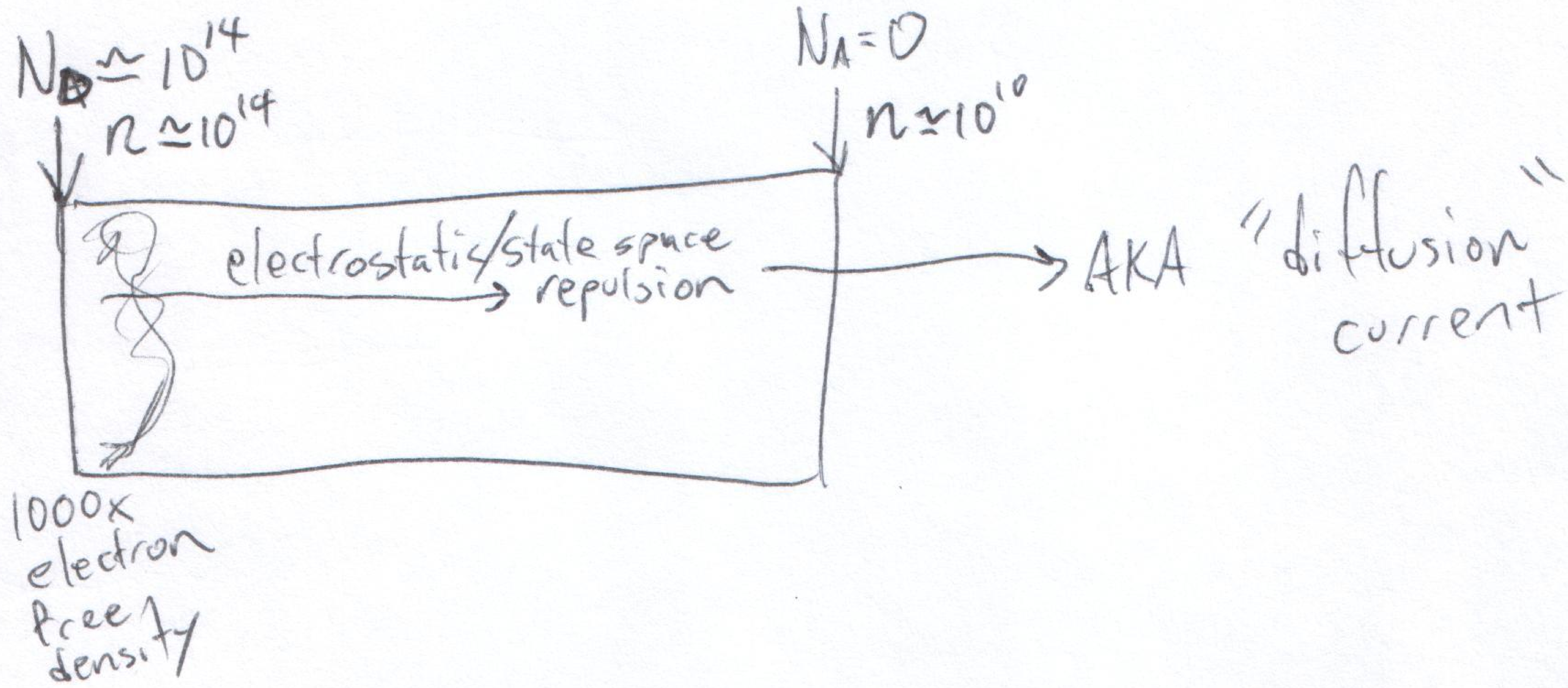
$10^{15} \cdot 10^{5} = 10^{20}$ $\quad 10^{15} + 10^{5} \simeq 10^{15}$

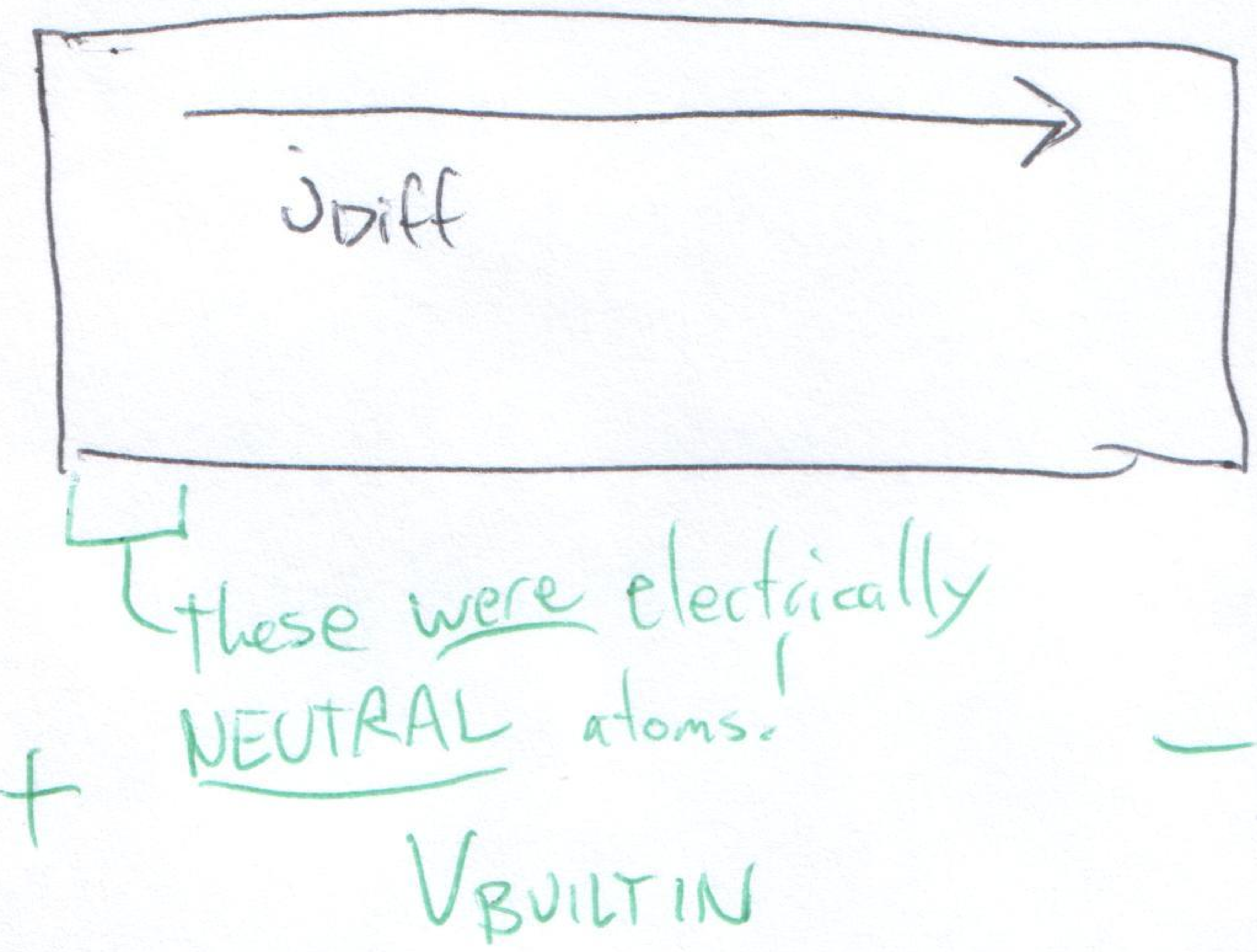
$10^{5} \cdot 10^{15} = 10^{20}$ $\quad 10^{5} + 10^{15} \simeq 10^{15}$

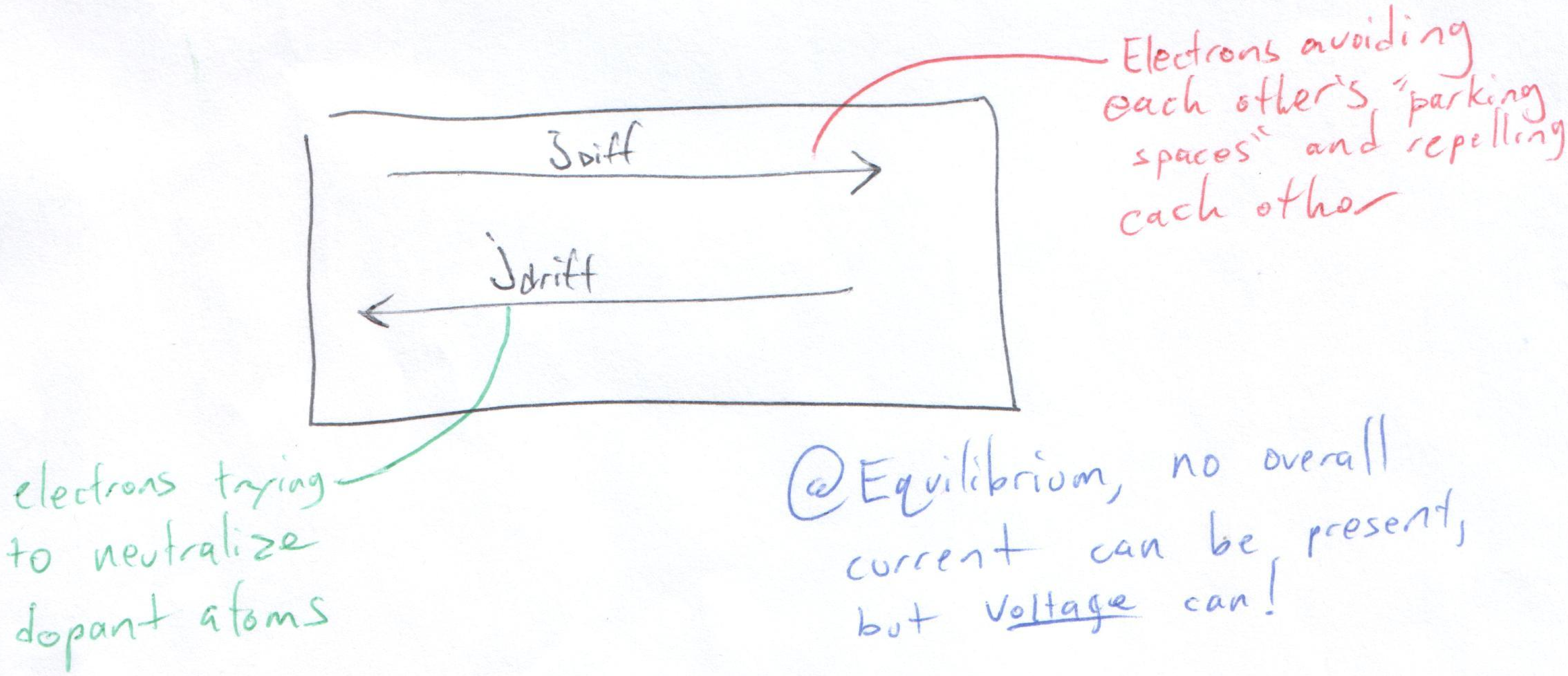
$10^{10} \cdot 10^{10} = 10^{20}$ $\quad 10^{10} + 10^{10} \simeq 10^{10}$

Imbalance in carriers makes for <u>more</u> carriers!

Drift, Diffusion & A block of silicon that thinks it's some kind of battery.

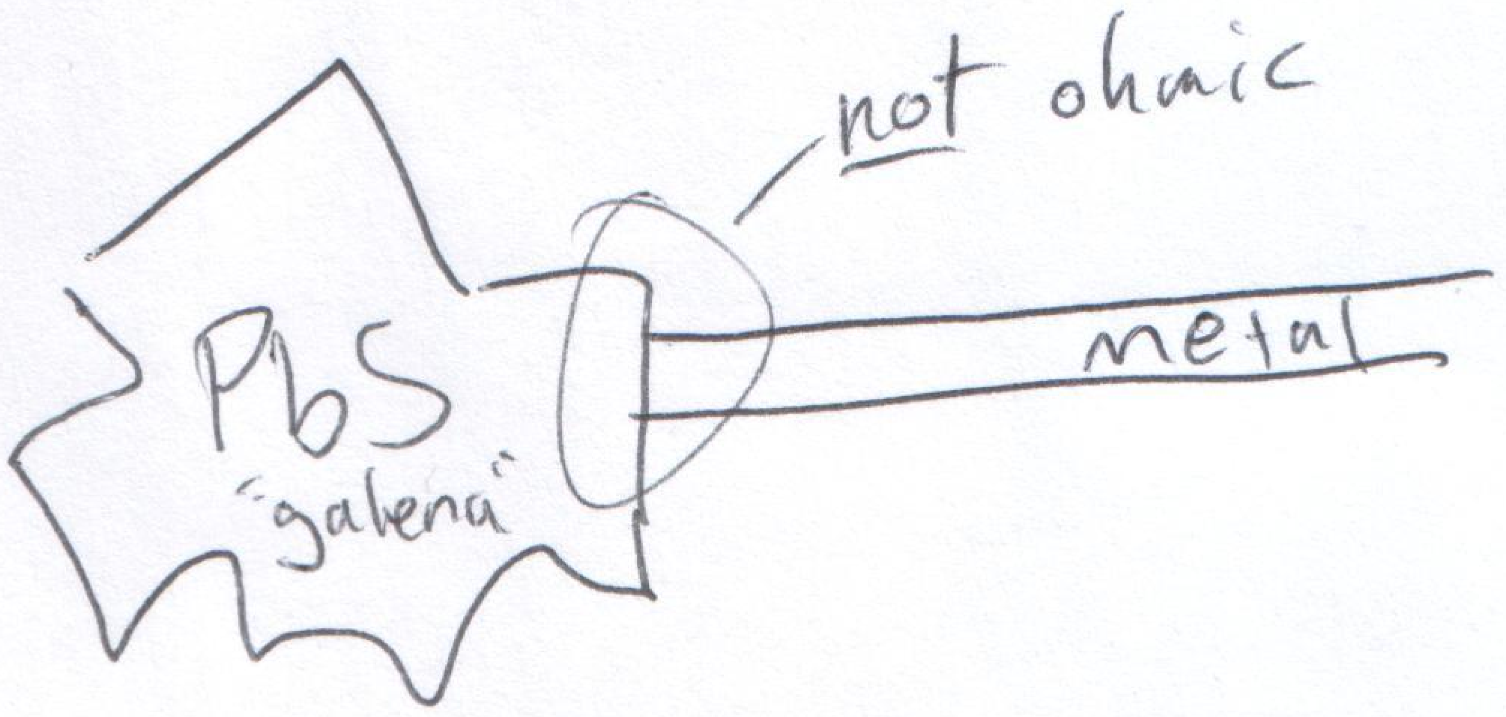


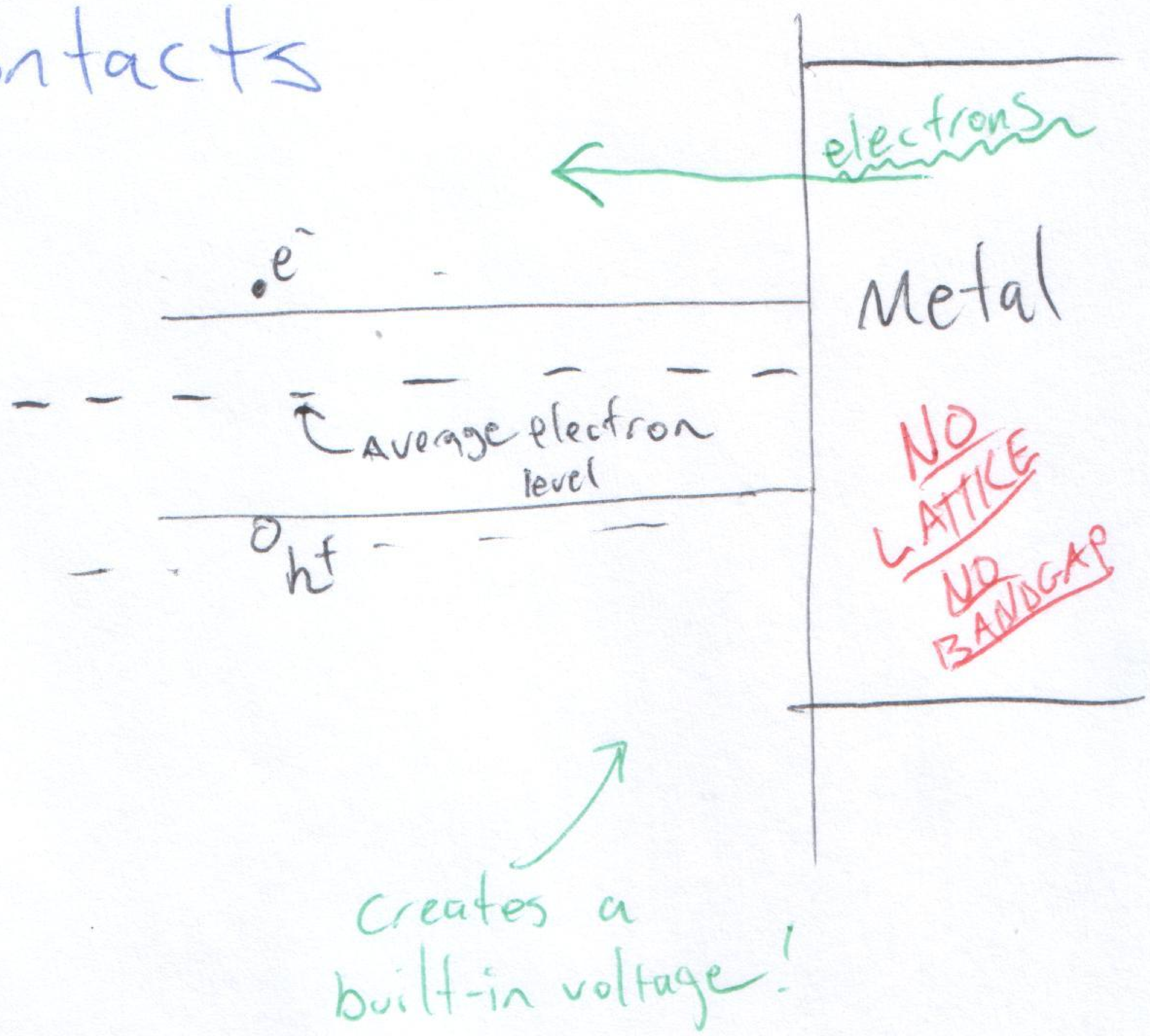




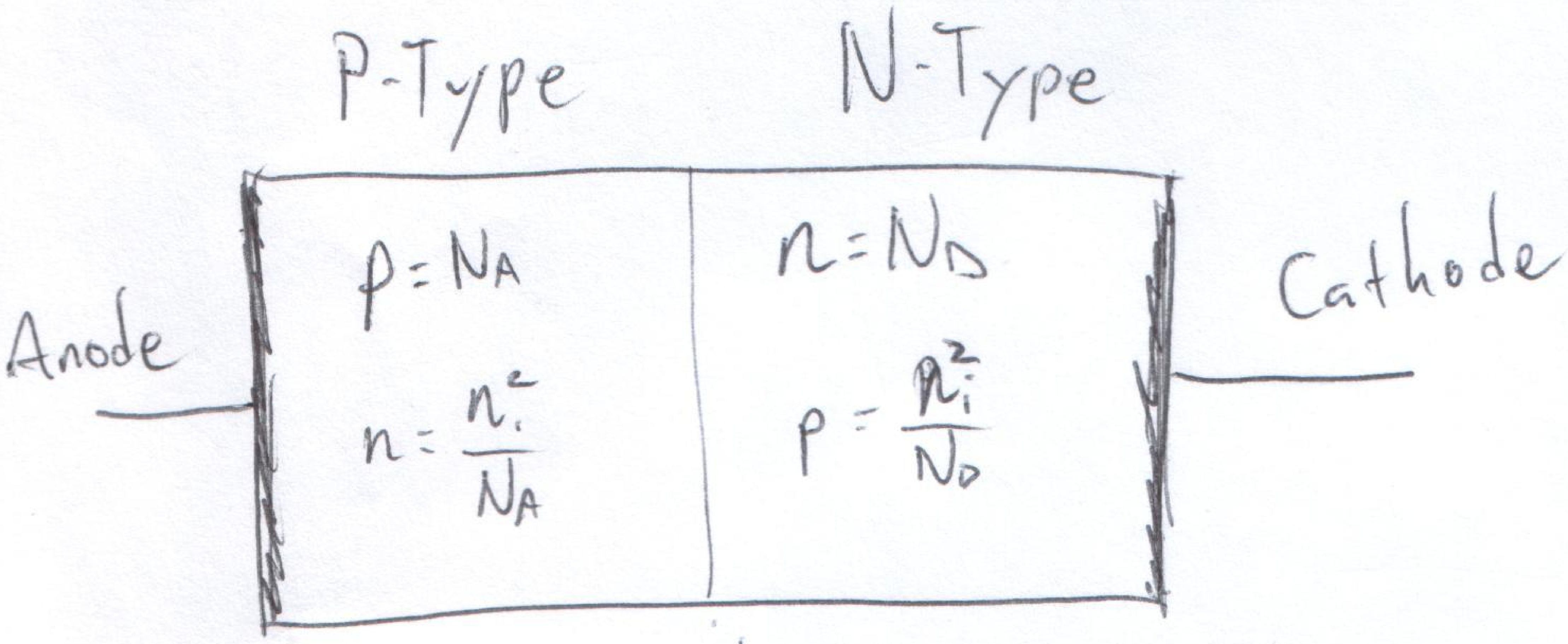
@Equilibrium, no overall current can be present, but voltage can!

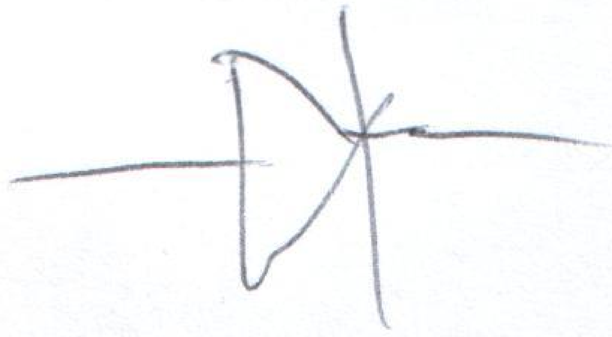
Aside Note: "Ohmic" Contacts



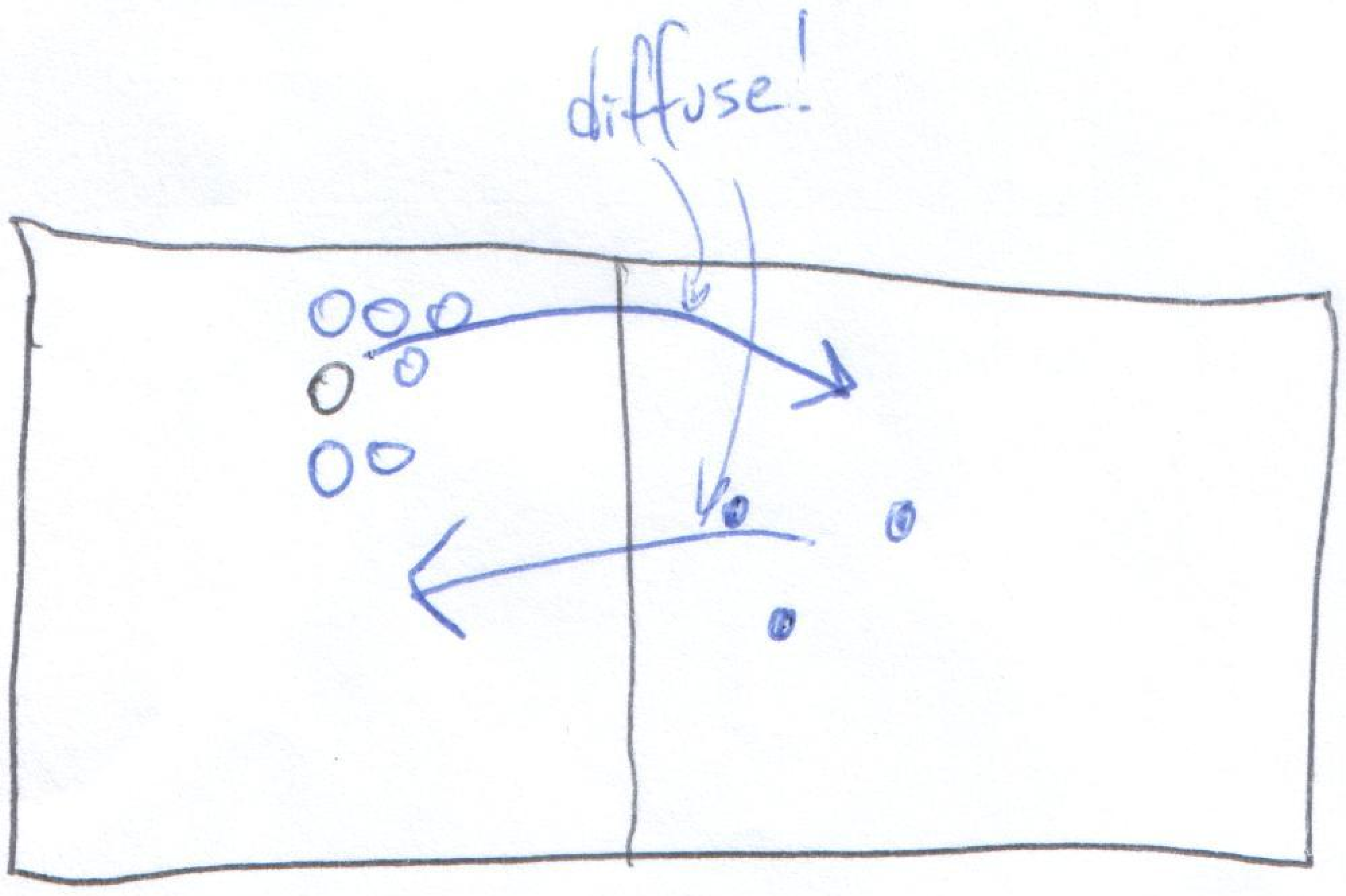


Ohmic Contacts must be designed into a process by tweaking the doping levels. (we will assume this was done.)

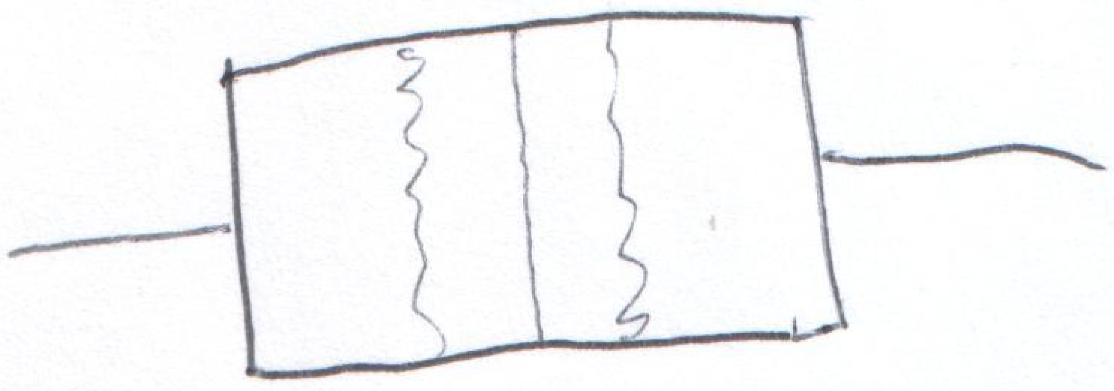


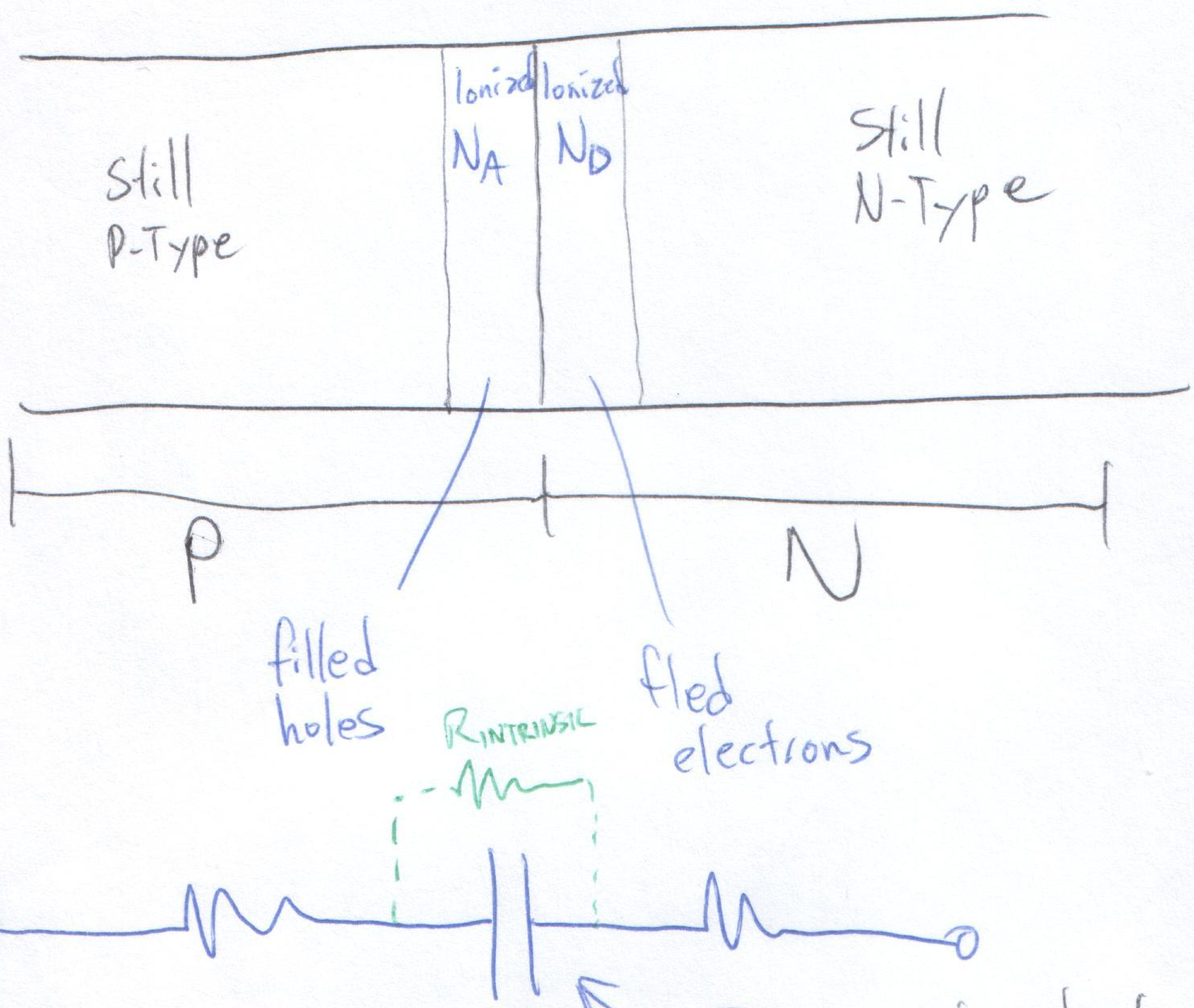


... ever see "Braveheart"?



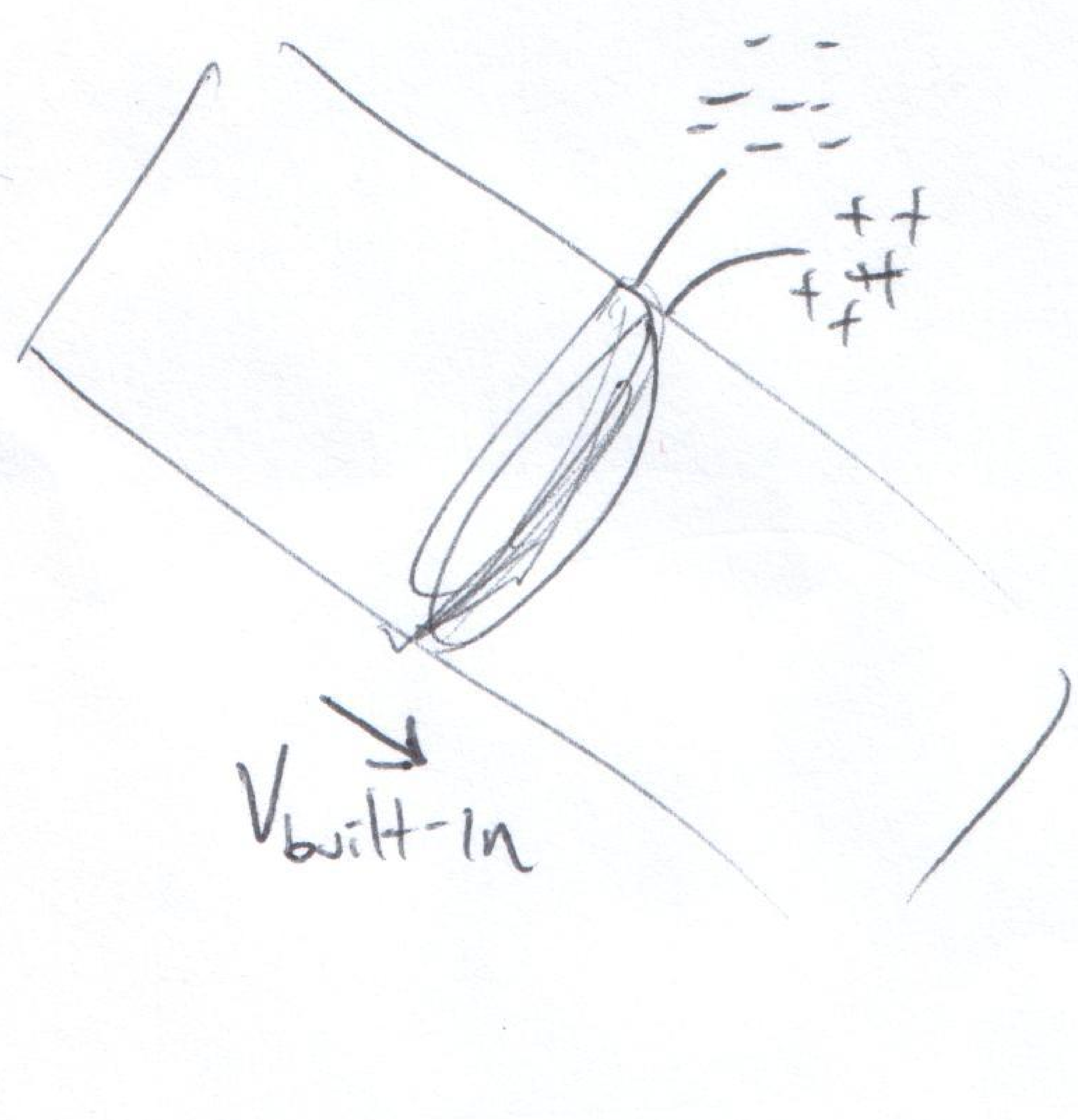
when the dust settles, electrons & holes have canceled each other out:





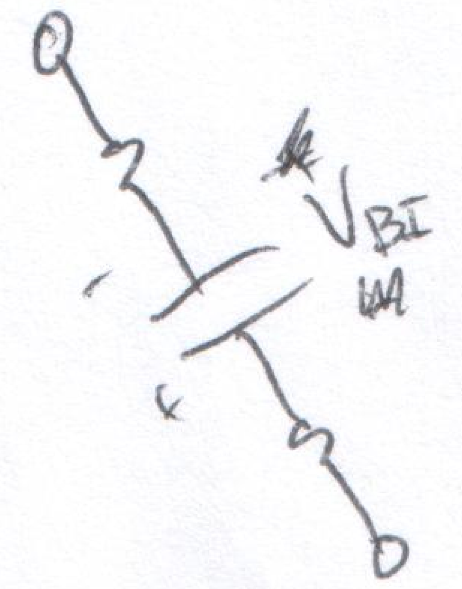
This semiconductor junction has just SPROUTED A CAPACITOR

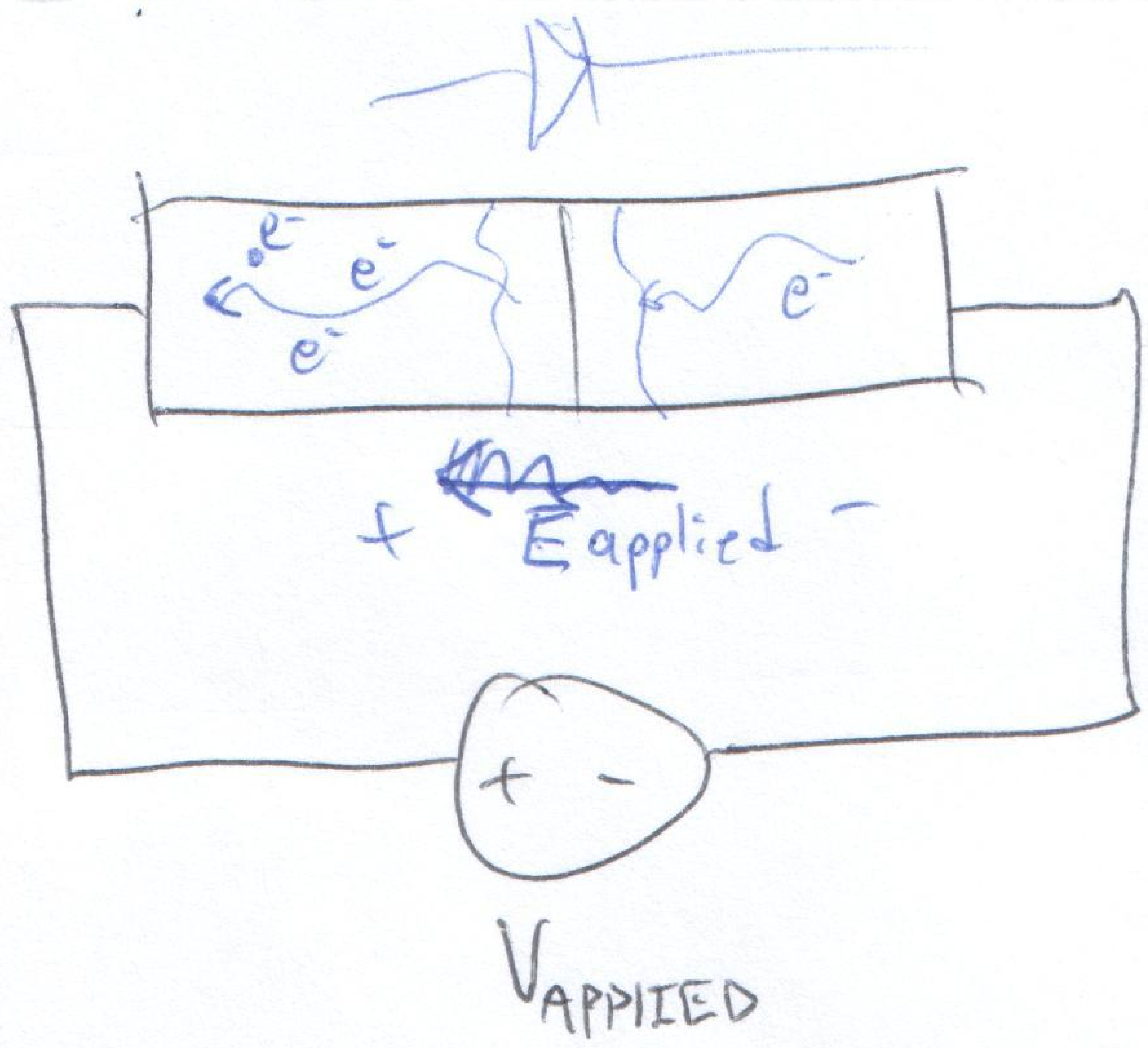
So that's weird, let's make it worse:

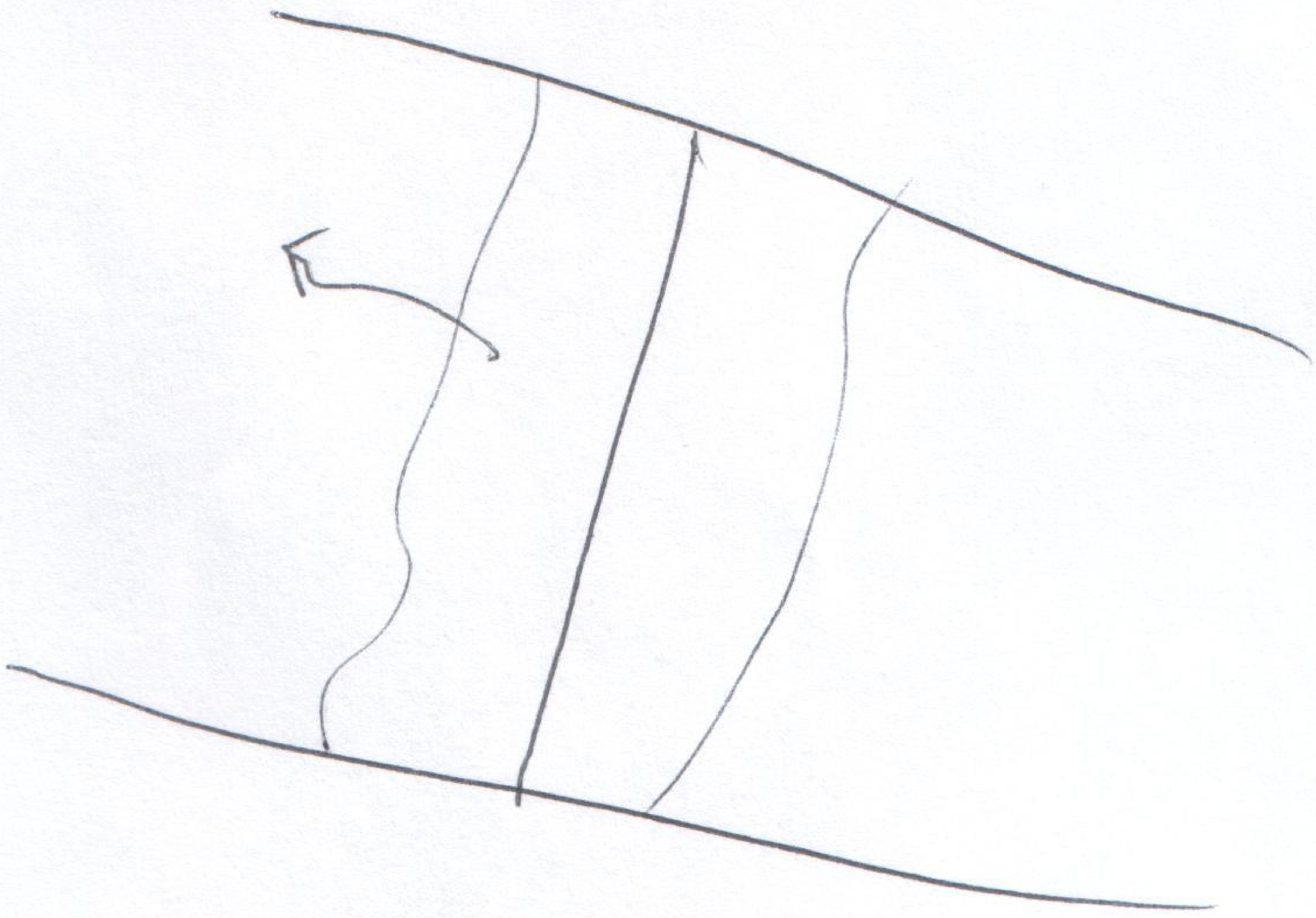


Just like the unevenly-doped slab, this has a built-in voltage, analagous to a charged capacitor, but more COMPLEX than that because charge.

Ok....



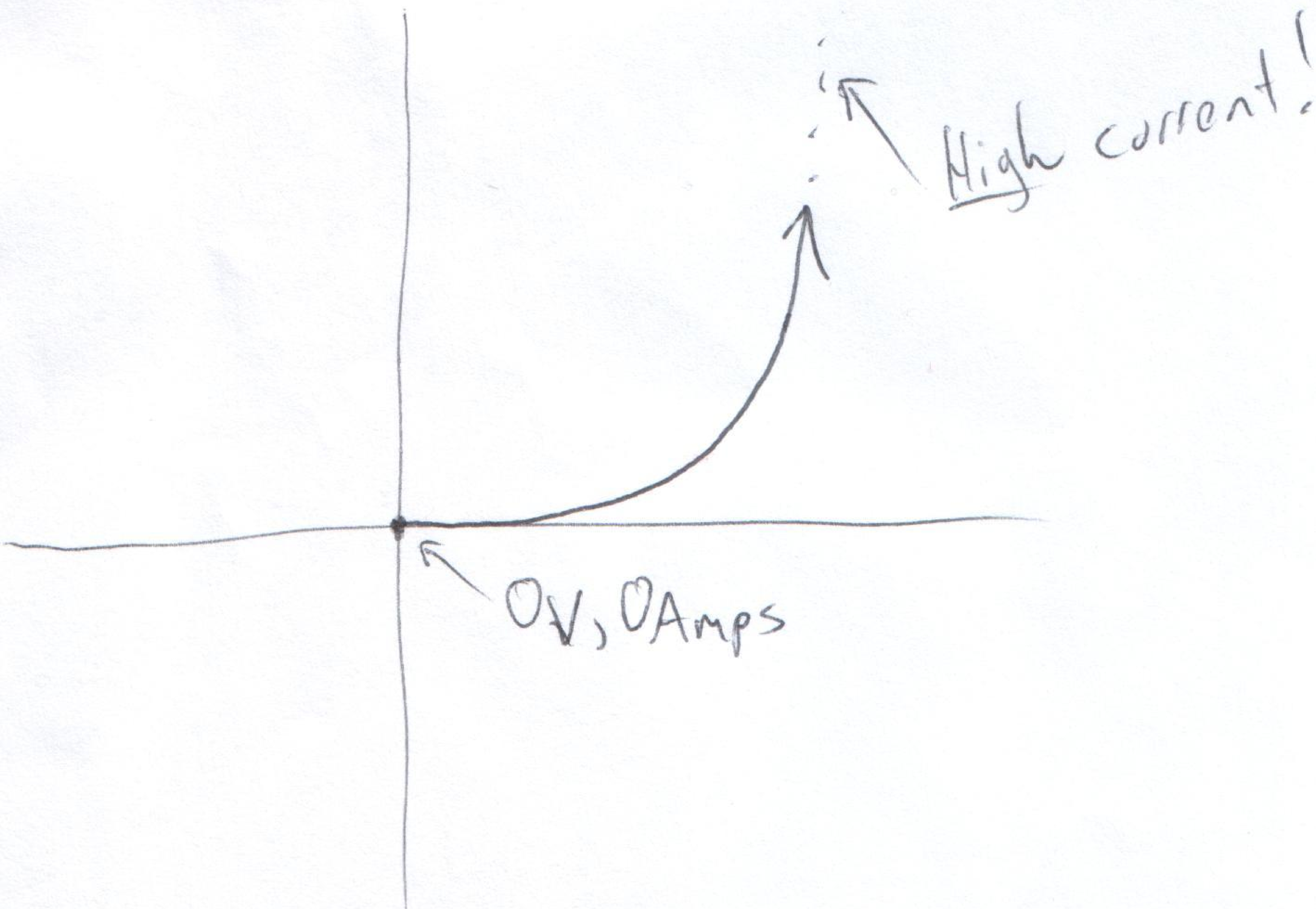




electrons leave the p-type side for the battery, de-ionizing Acceptors.

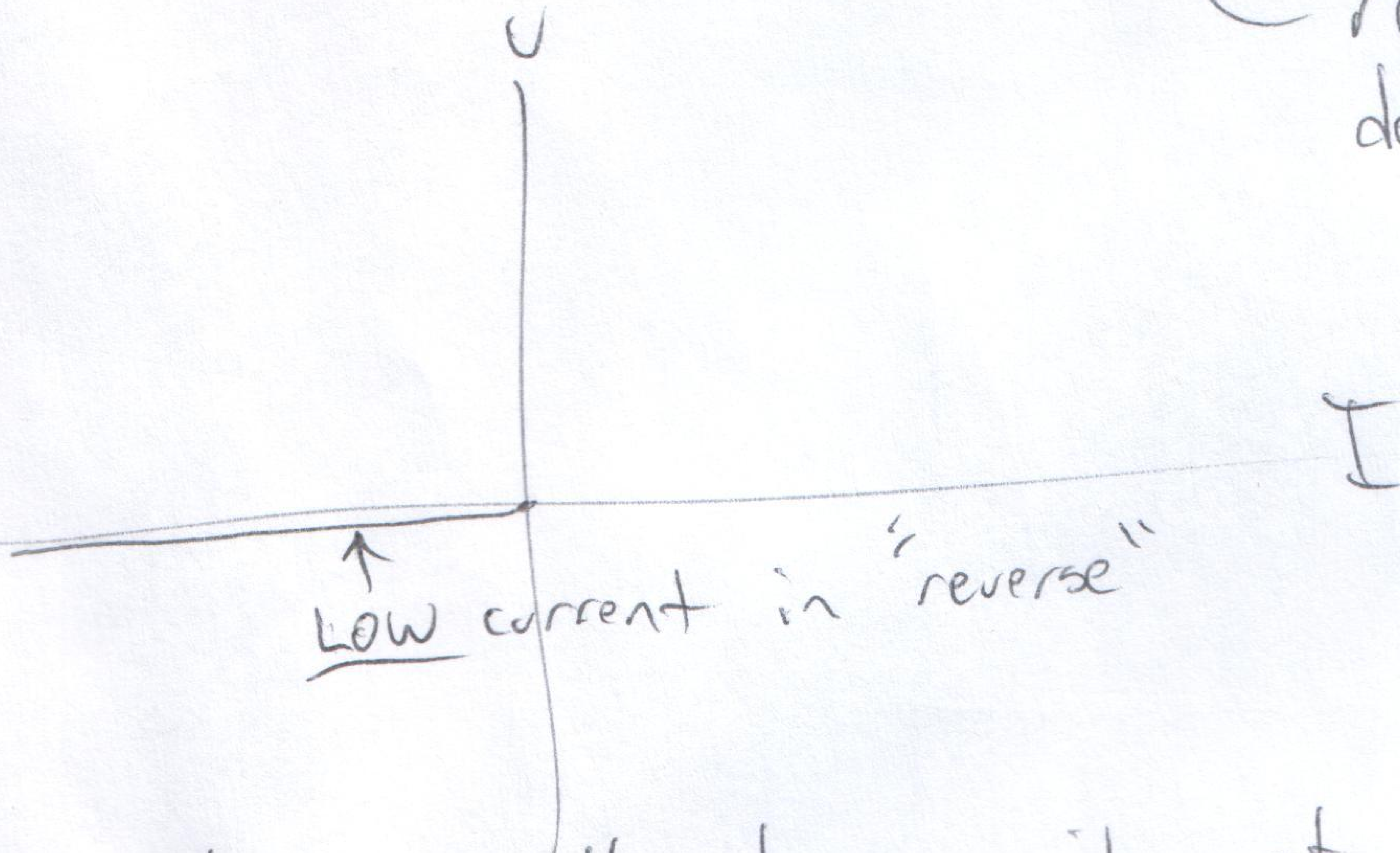
Now need fewer ionized Donors to fill the hole.

- As the "capacitor" is "discharged" (note, this doesn't mean it's zero at zero volts across it, diodes are weird) the distance covered by this region shrinks.
- Eventually the distance drops to zero and conduction gets even faster.



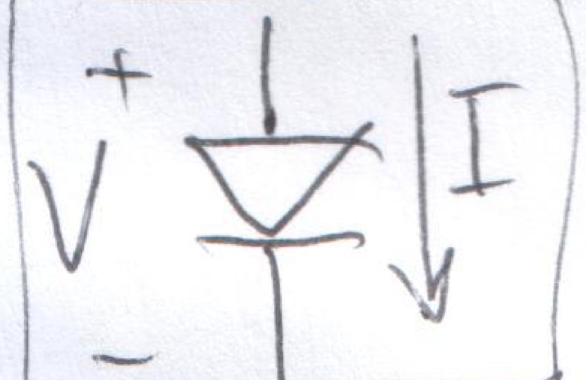
Applied Voltage in the other direction has the <u>opposite effect</u> as electrons stuff in on the far side:

requiring <u>more</u> ionized donors to compensate



<u>LOW</u> current in "reverse"

for today, we'll leave it at this, with the following equation:



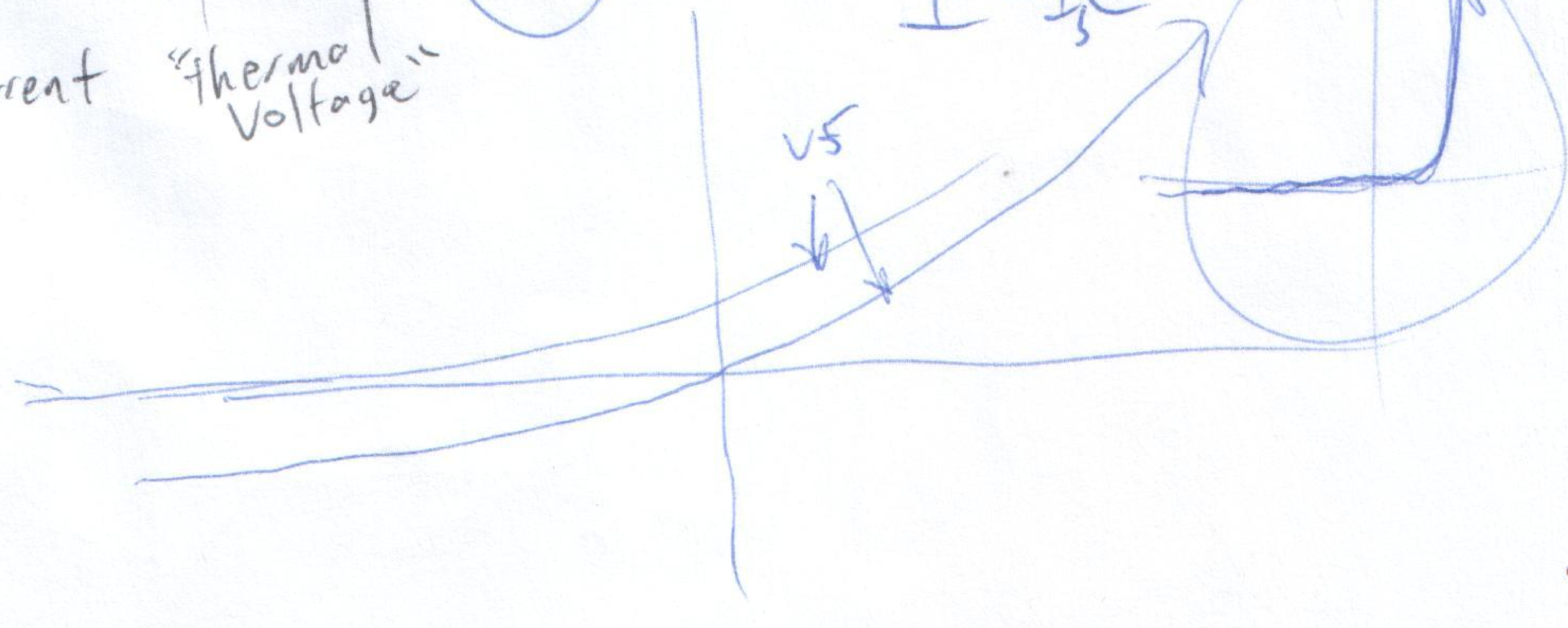
$$I = I_s\left(e^{V/V_T} - 1\right)$$

Const, Leakage current

"thermal Voltage"

this one exists to pin $e^0 - 1 = 0$ for current, so usually we can say:

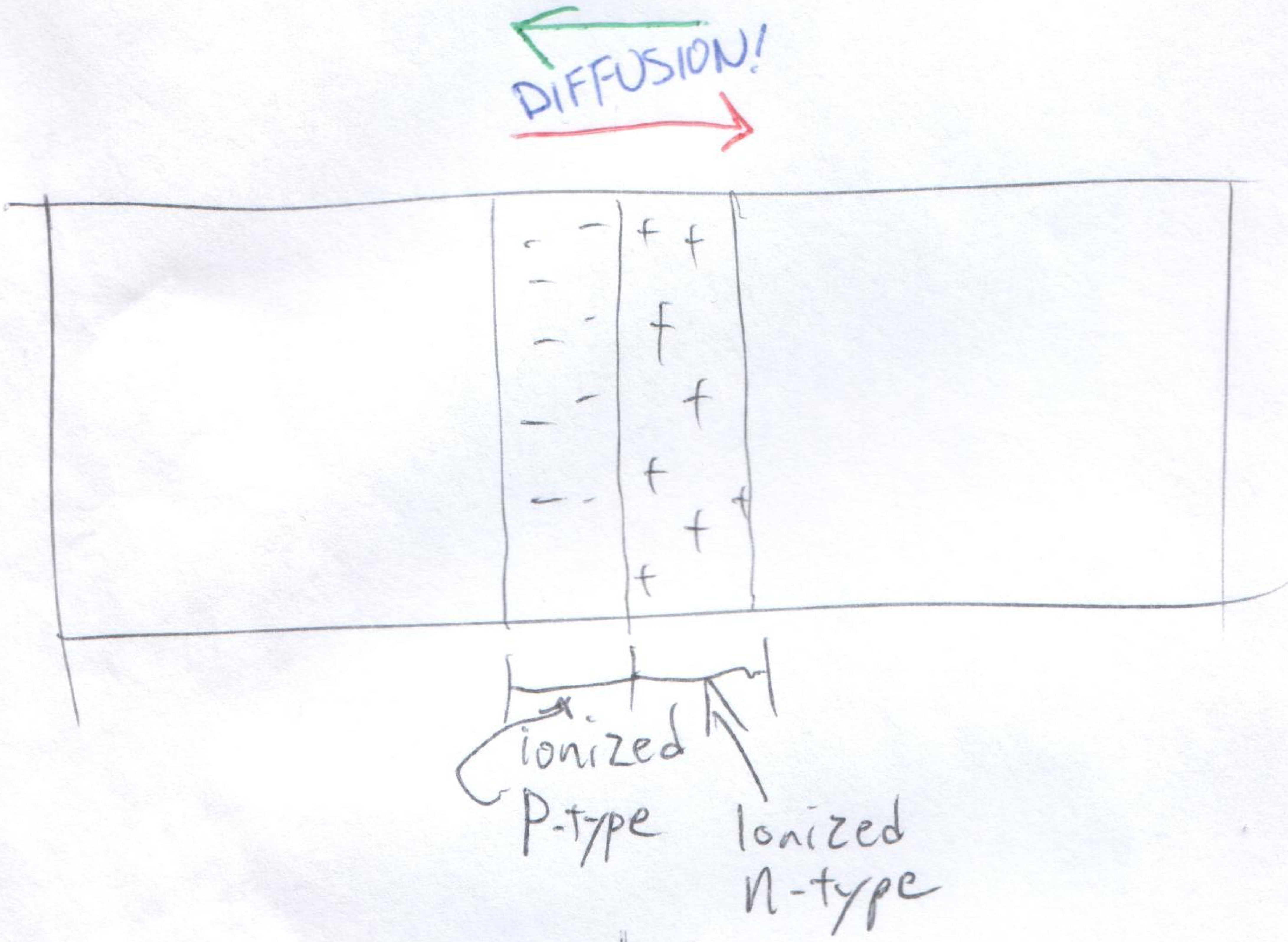
$$I = I_s e^{V/V_T}$$

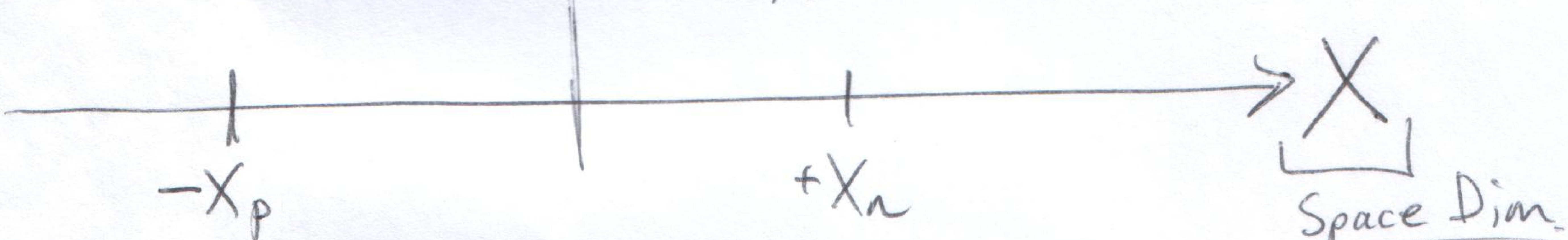


Note: V_{BI} is only not disturbed if applied Voltage is also V_{BI}.

Textbook's example of a Diode:

$N_A \cong p_p = 10^{17}\ h/cm^3$	$N_D \cong n_n = 10^{16}\ e/cm^3$
$n_p = \frac{n_i^2}{N_A}$	$p_n = \frac{n_i^2}{N_D}$

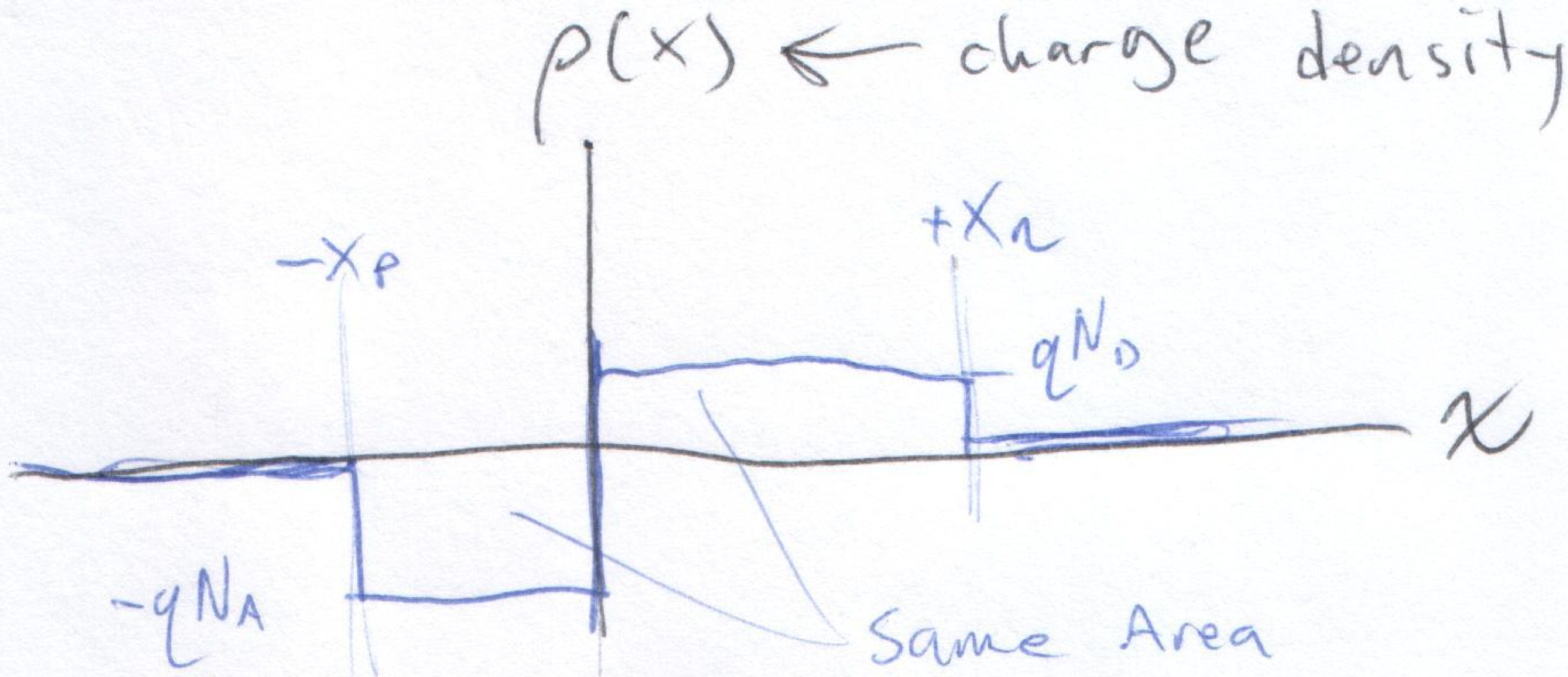




each region will have the same # of charges:

$$qN_A x_p = qN_D x_n$$

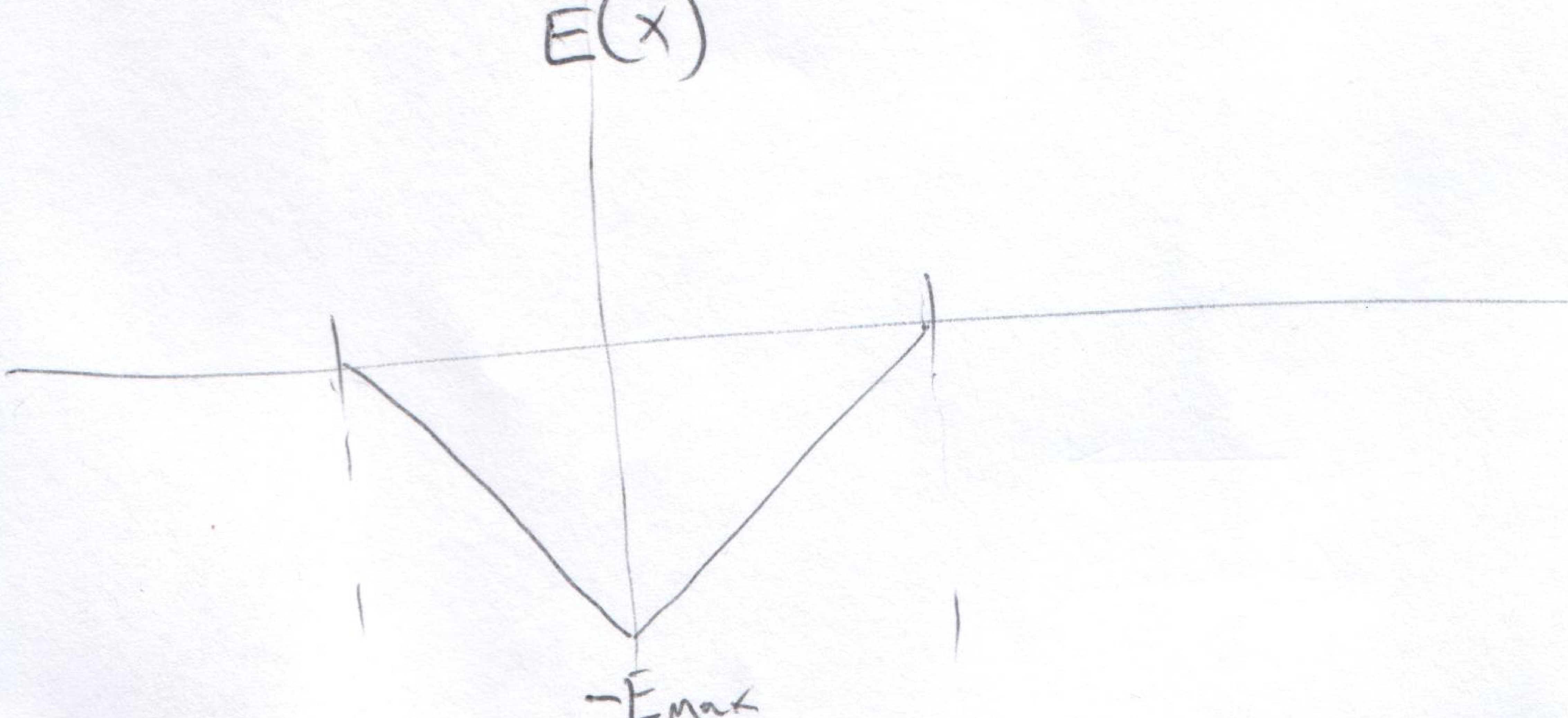
$\boxed{\text{Note! this relates } x_p \,\&\, x_n \text{ to each other, but won't help you find } x_p \text{ or } x_n \text{ if you don't have at least one! PROBLEM.}}$



One of Maxwell's equations actually applies here: $\nabla \cdot E = \frac{\rho}{\varepsilon_s}$

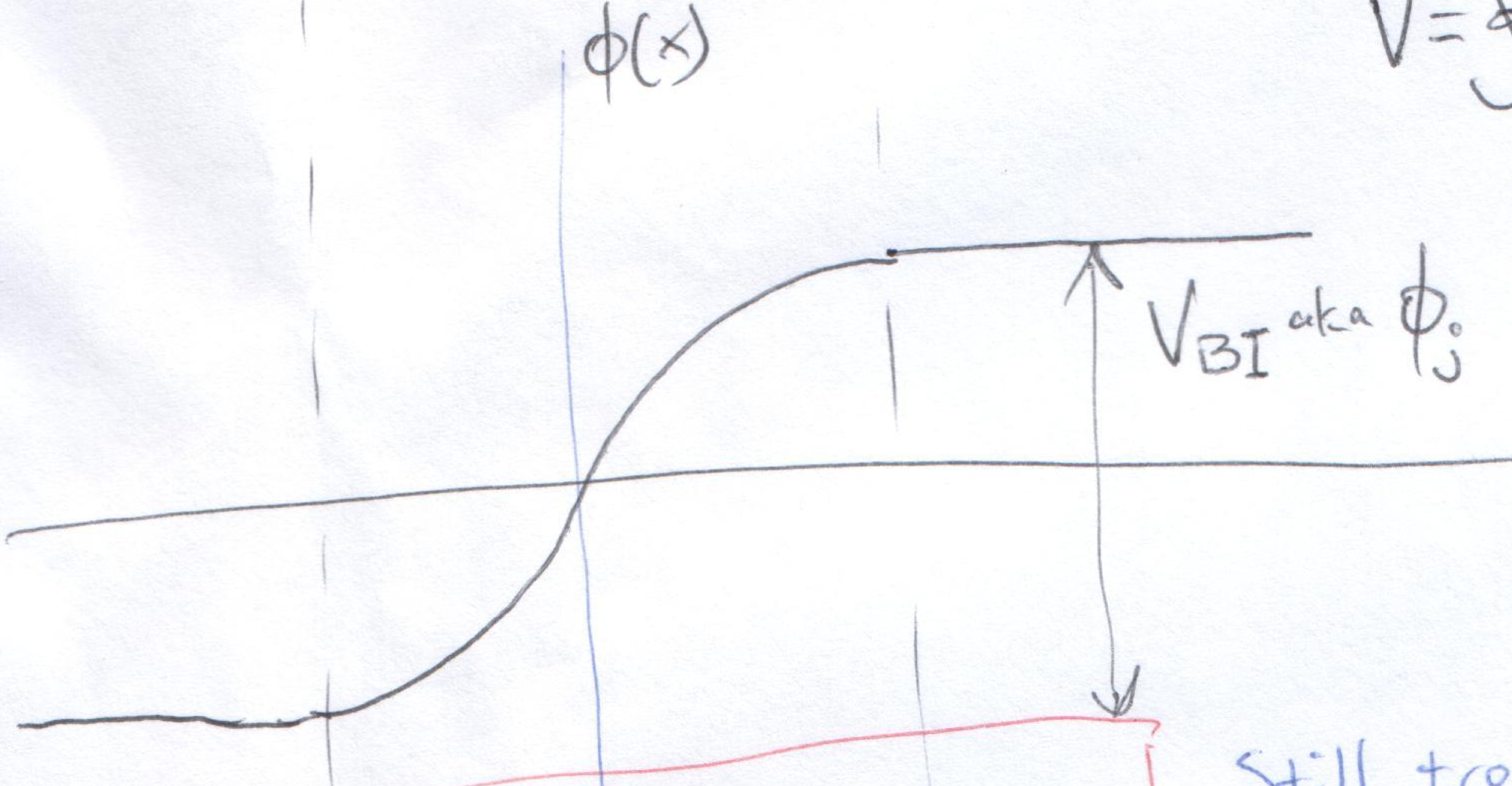
In a straight line, this can reduce down to:

$$E(x) = \frac{1}{\varepsilon_s} \int \rho(x)\,dx$$



Naturally the E-field is biggest at the interface, essentially two big ionized blobs pulling on each other

$V = \int E$] definition of voltage



Integrating twice gives built-in voltage.

The ugly, awful, cheap trick that would never fly in any journal ever:

$$\phi_j = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

pulled out of SOME OTHER BOOK with ZERO explanation!

Still troubling but at least believable:

$$W_{d0} = (x_n + X_p) = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\phi_j}$$

$$V_T = \frac{kT}{q}$$

Balancing Diffusion & Drift:

~~Diffusion:~~ Drift: $\vec{j} = q \cdot \# \cdot \mu \cdot \vec{E}$

Diffusion: $\vec{j} = q D \underbrace{\nabla \cdot \#}_{\text{gradient}}$

$\boxed{D = \mu \frac{kT}{q}}$

Einstein's Relationship

$$j_n = 0 = q n \mu_n E + q D_n \frac{\partial n}{\partial x} = 0$$

$$nE + V_T \frac{\partial n}{\partial x} = 0$$] 1st order diff eq in x ?

Labs this week: get your kits in EEB134

The website will soon be updated with lab notes!

Bring cash in case you need
- DMM
- wire
- Probes
- Breadboards!

We're about to leave physics and chemistry behind for a while, but we'll be back for MOSFETs, so, let's review key points:

- in semiconductors, conduction is <u>DRIFT</u> CURRENT, $j = q \cdot \# \cdot \mu \cdot E$
- <u>concentration gradients</u> will cause DIFFUSION CURRENT, $j = q \cdot \cancel{\#} \cdot \mu \cdot V_T \cdot \frac{\partial \#}{\partial x}$
- <u>all</u> gradients will cause non-ohmic effects, but diode junctions especially will have exponential ASYMMETRIC behavior!

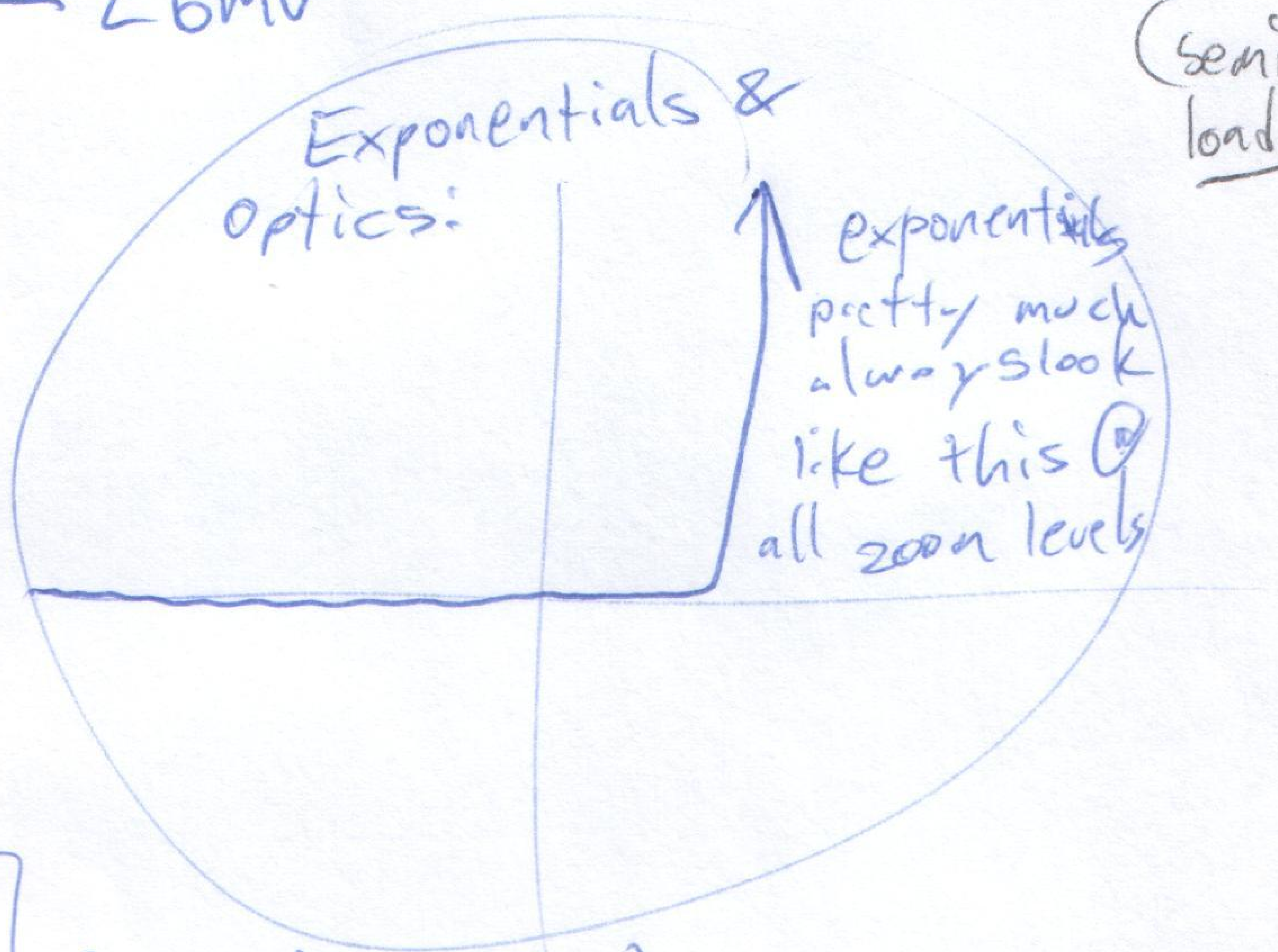
Above all, remember that the essence of semiconductors is that CARRIER CONCENTRATIONS can be ALTERED to control CONDUCTION.

Now, circuits. $I = I_s\left(e^{V/nV_T} - 1\right)$

n: a dimensionless fudge factor (semiconductors are loaded with these.)

V_T in silicon: $\simeq 26\text{mV}$

$\underbrace{10^{-18} \leq I_s \leq 10^{-9}}_{\text{faaantastic}}$

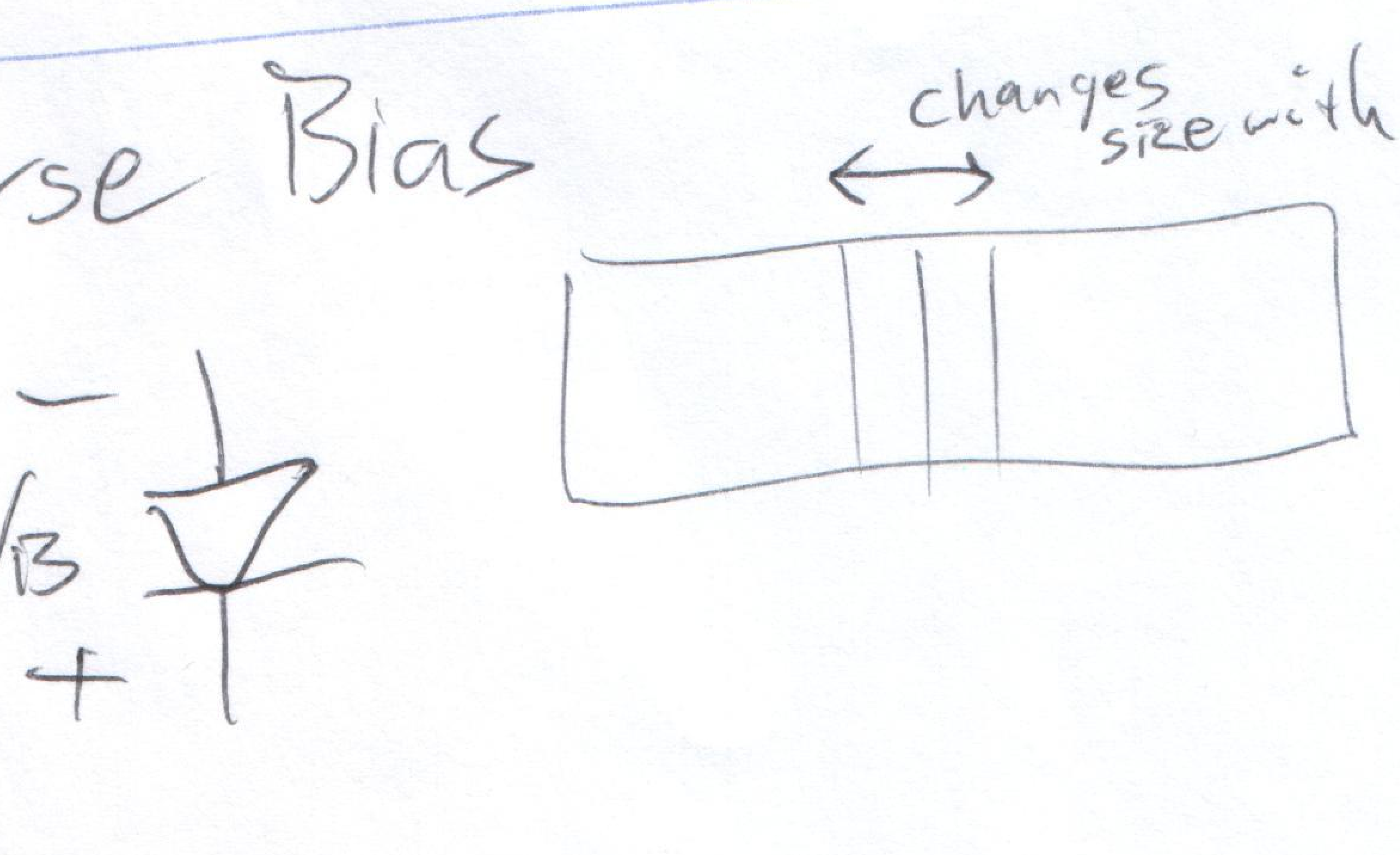


$$I = I_s e^{V/V_T} \quad \text{(roughly true)}$$

$$\ln \frac{I}{I_s} = \frac{V}{V_T} \qquad V = \underbrace{V_T}_{\text{temperature dependent!}} \ln \frac{I}{I_s}$$

Also temp dependent, so unfortunately $V \neq PTAT$

In Reverse Bias



variable C?