Design of an Electrically Operated mid-infrared solid-state modulator

AITA

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Outline

- Background
- Choice of Material
- The physics
- Electrical modulator
- Design criteria
- Simulation results
- Outlook

The need for a modulator

- Built in calibration, ‘thermal referencing’
- Variable IR transmission in situations where mechanical solutions are undesirable
- Image from pyroelectric detectors requires modulation
- IR Spatial Light Modulators?

Desiderata!

- Polarisation insensitive
- Copes with low F number beams, to F#1
- High on state transmission (>95%)
- Low power consumption
- High off state attenuation
- Large aperture (to $1cm^2$)
- Full 8-14μm band
- Fast – but slow OK for many applications.

Difficult to satisfy simultaneously!

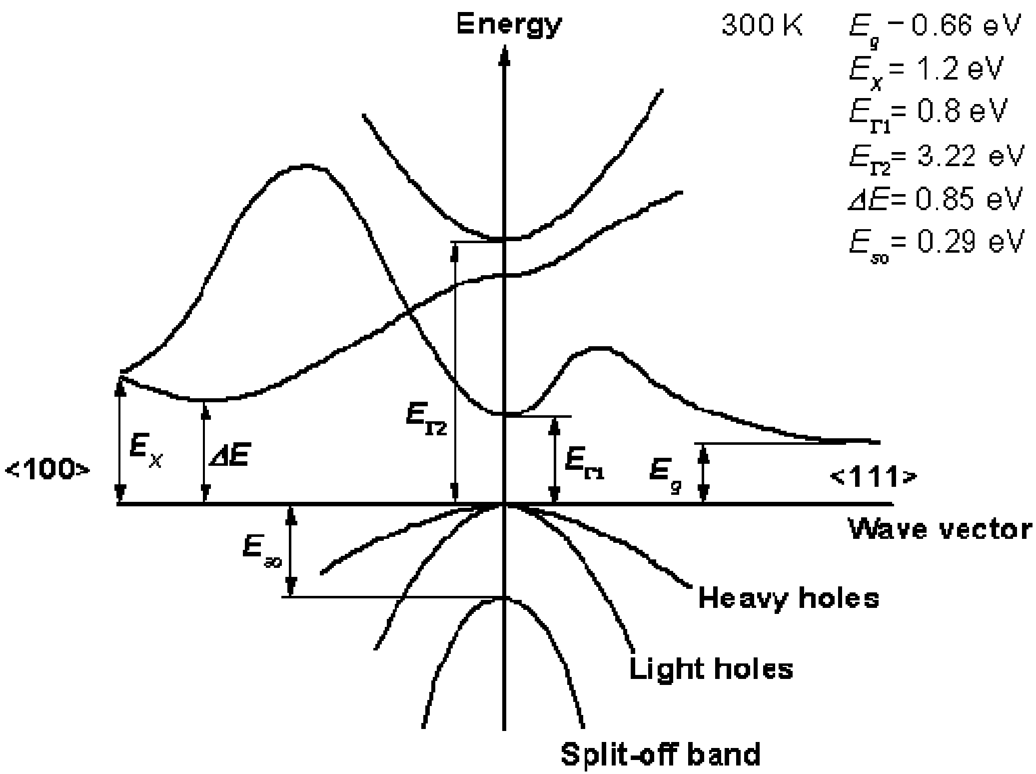
For a semiconductor, carrier based device we need:

- A stronger absorption mechanism than the free-carrier Drude-Zener
- A way to maintain large carrier densities at low power cost
- Hence a long lifetime
- Infrared transparency
- Availability!

Choice of Material

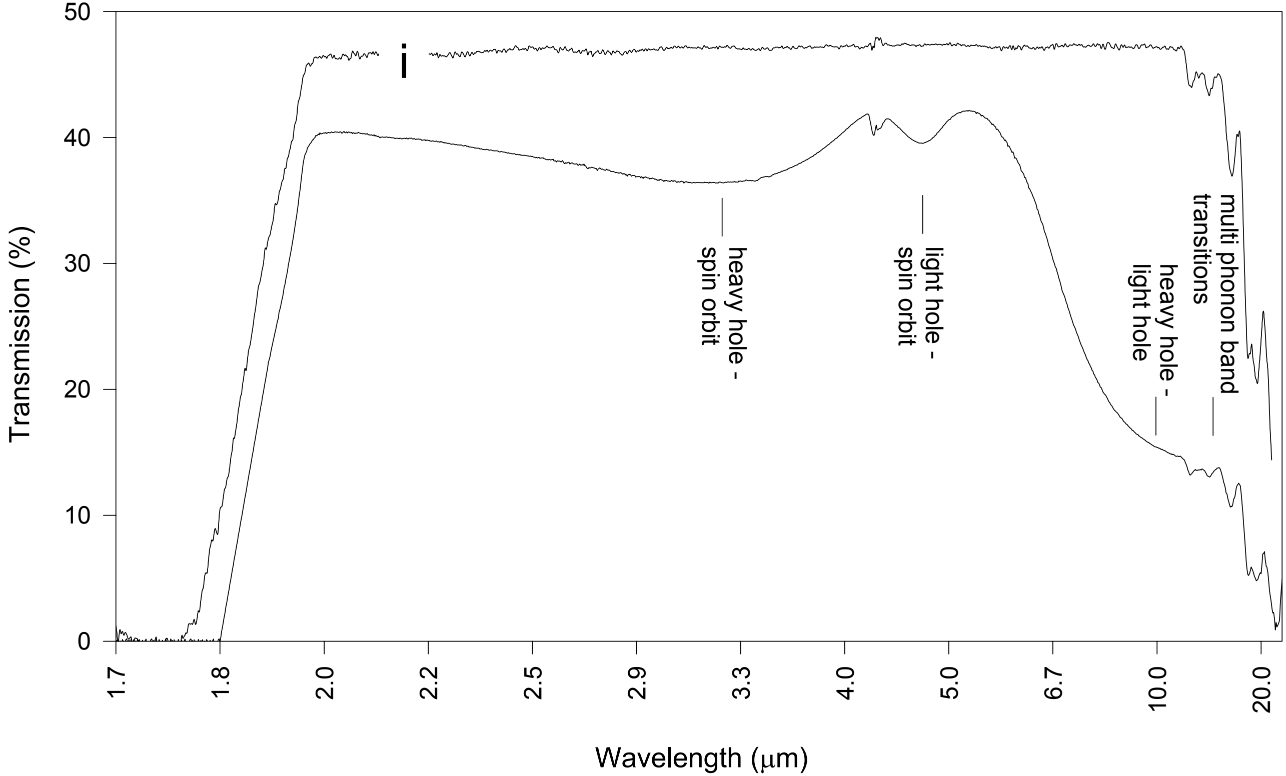
- Why Ge
  - Indirect bandgap – long intrinsic lifetime
  - IR transparent 1.8—18 um
  - Available in high purity (use in Nuc. Det.)
  - High carrier mobility
  - Availability + cost + ease of fabrication
  - **p-type Ge has lh-hh interband transitions in required spectral range**

The principle



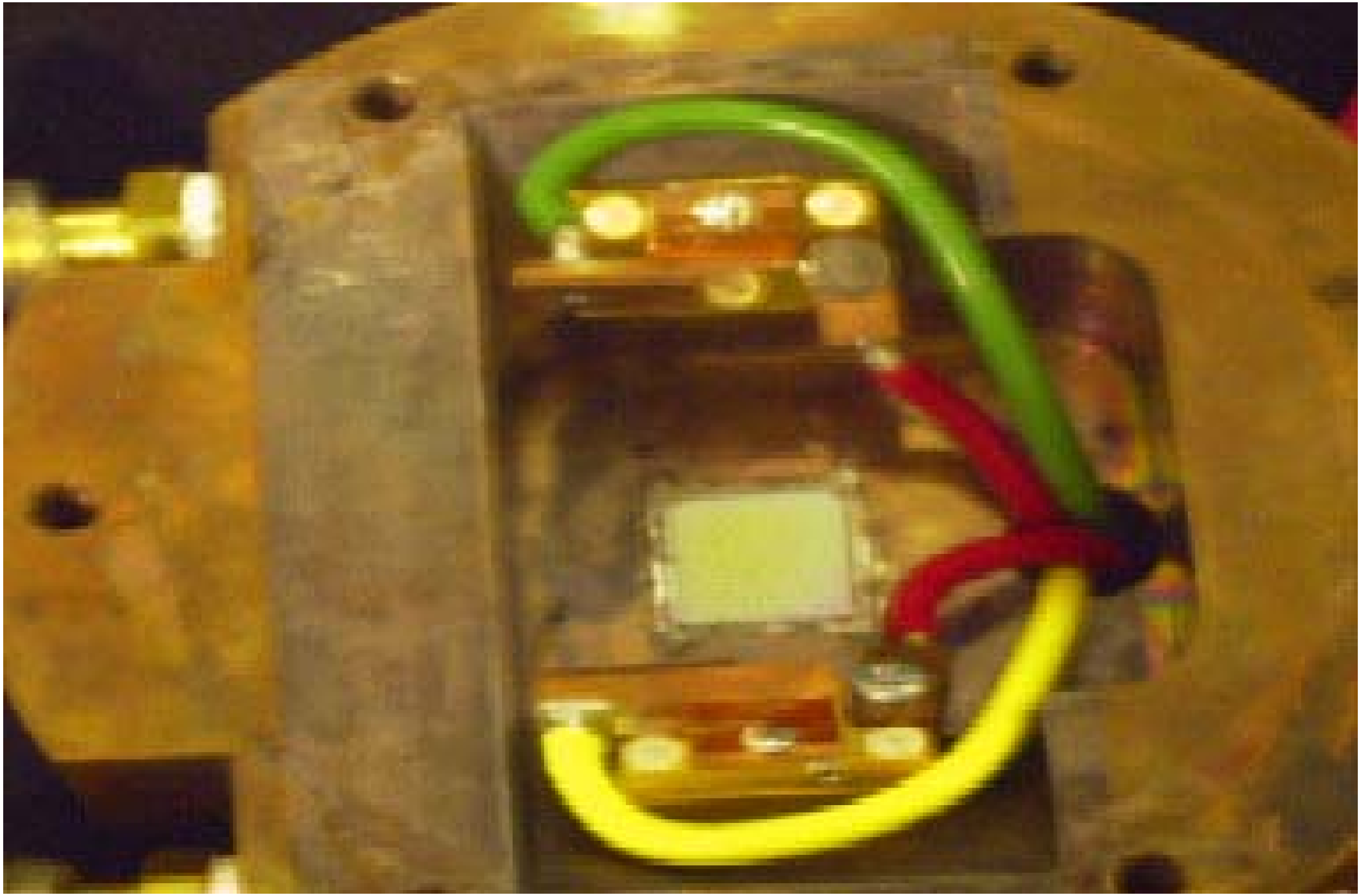
Band diagram of Ge showing heavy and light hole band

Absorption spectra



Absorption spectra of intrinsic and p type Ge

Optical modulator



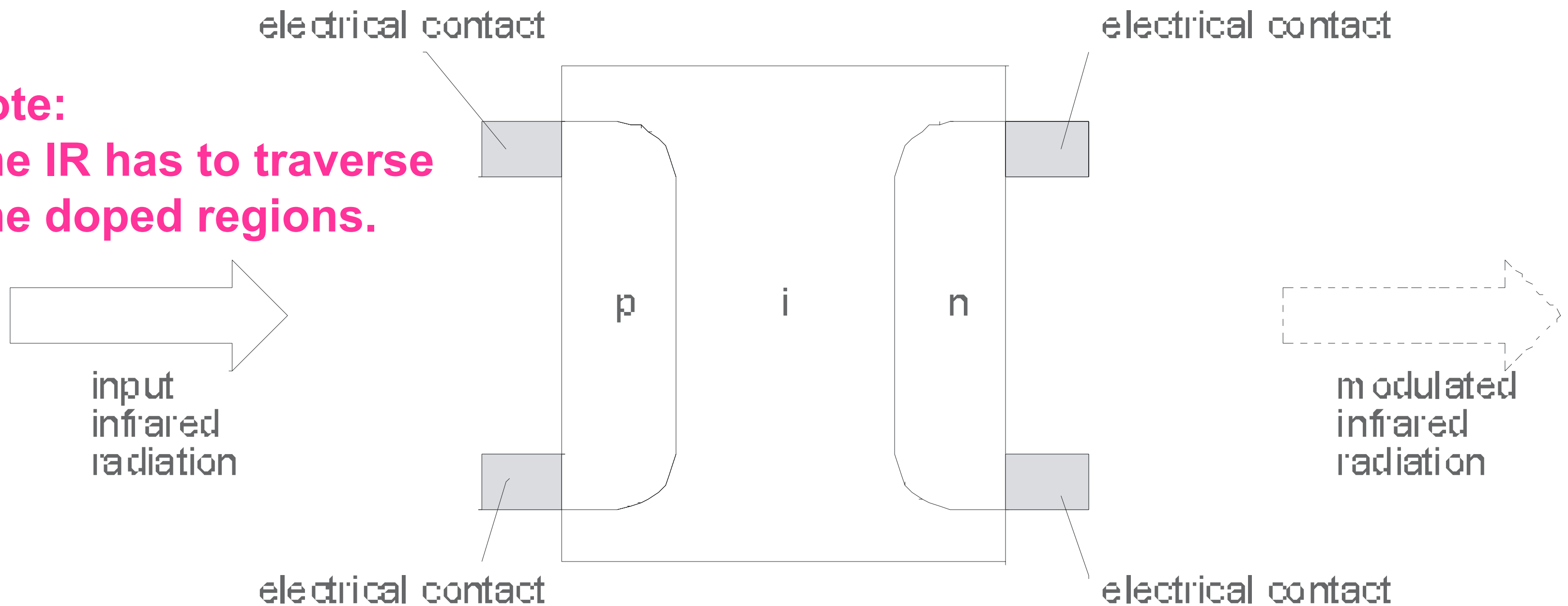
Optical Modulator in action

Off state

ON state

Basic structure

Note:
The IR has to traverse
The doped regions.



Optimise:
- Doping levels
- Width of p, i, and n regions etc
- Processing

Design Criteria

OPTICAL ON state (diode electrically off)

$$T_{on}=T_o\,\exp(-A) = T_0\,\exp -(N_p{*}x_p{*}\sigma_h)$$

OPTICAL OFF state (diode electrically on)

$$T_{off}=T_o\,\exp(-A) = T_0\,\exp(n_p{*}\sigma_h)$$

$$[n_p=\int_0^t c_p(x)dx]$$

Where T_o=1 for 100% transmission

A is the absorption

σ_h is hole absorption cross-section ($5.33\times10^{-16}cm^2$)

N_p is the doping density for holes ($/cm^3$)

n_p is the area carrier density when forward biased (p+i region)

x_p is the thickness of the p layer

Design Criteria

- ON state: max T_{on} → minimum N_p*x_p
- OFF state: min T_{off} → maximum n_p
  Uniform current injection requires high doping density (N_p)

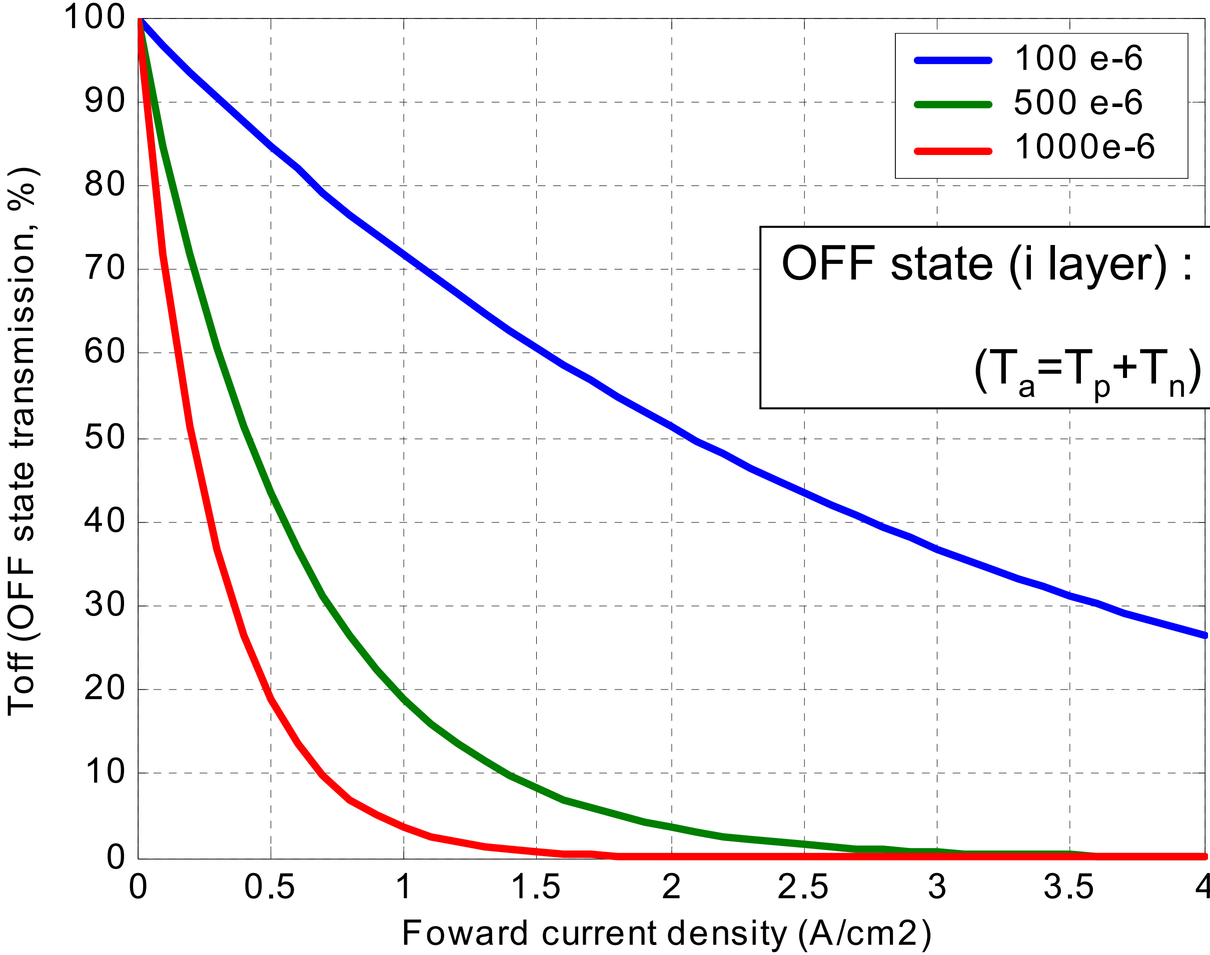
ABSORPTION vs UNIFORMITY trade-off!

Lifetime requirement

- We had σ_h =5.33x10^{-16}cm^2
- And $T_{off}=T_0 \exp(n_p * \sigma_h)$ $[n_p = \int_0^t c_p(x)dx]$
- Lets assume a uniform hole density
- And a 1mm thick device
- And require $T_{off}=0.01$ (ie, 1%)
- Then we need $n_p=8.64*10^{15}/cm^2$
- Or $N_p=8.64*10^{16}/cm^3$

Design Criteria: required lifetime

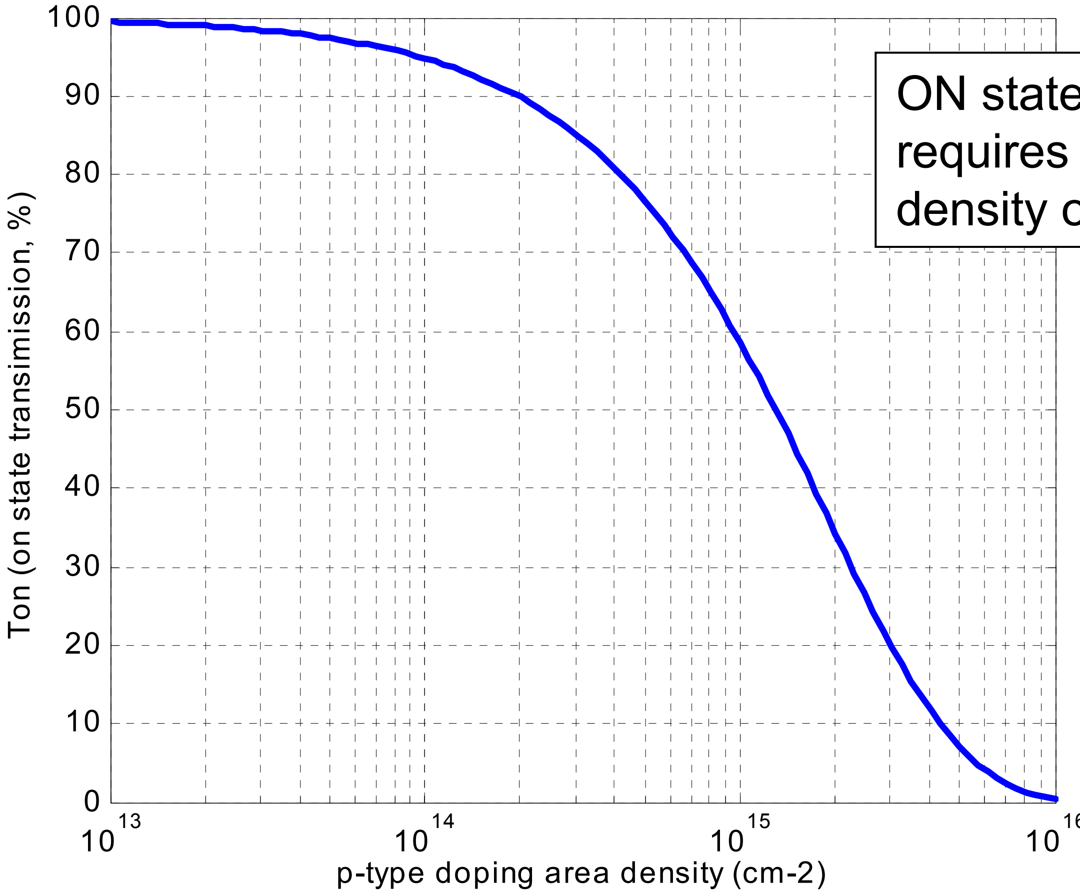
Rough analytical estimates:



OFF state (i layer) : $n_p = T_a * J/q$

$(T_a = T_p + T_n)$

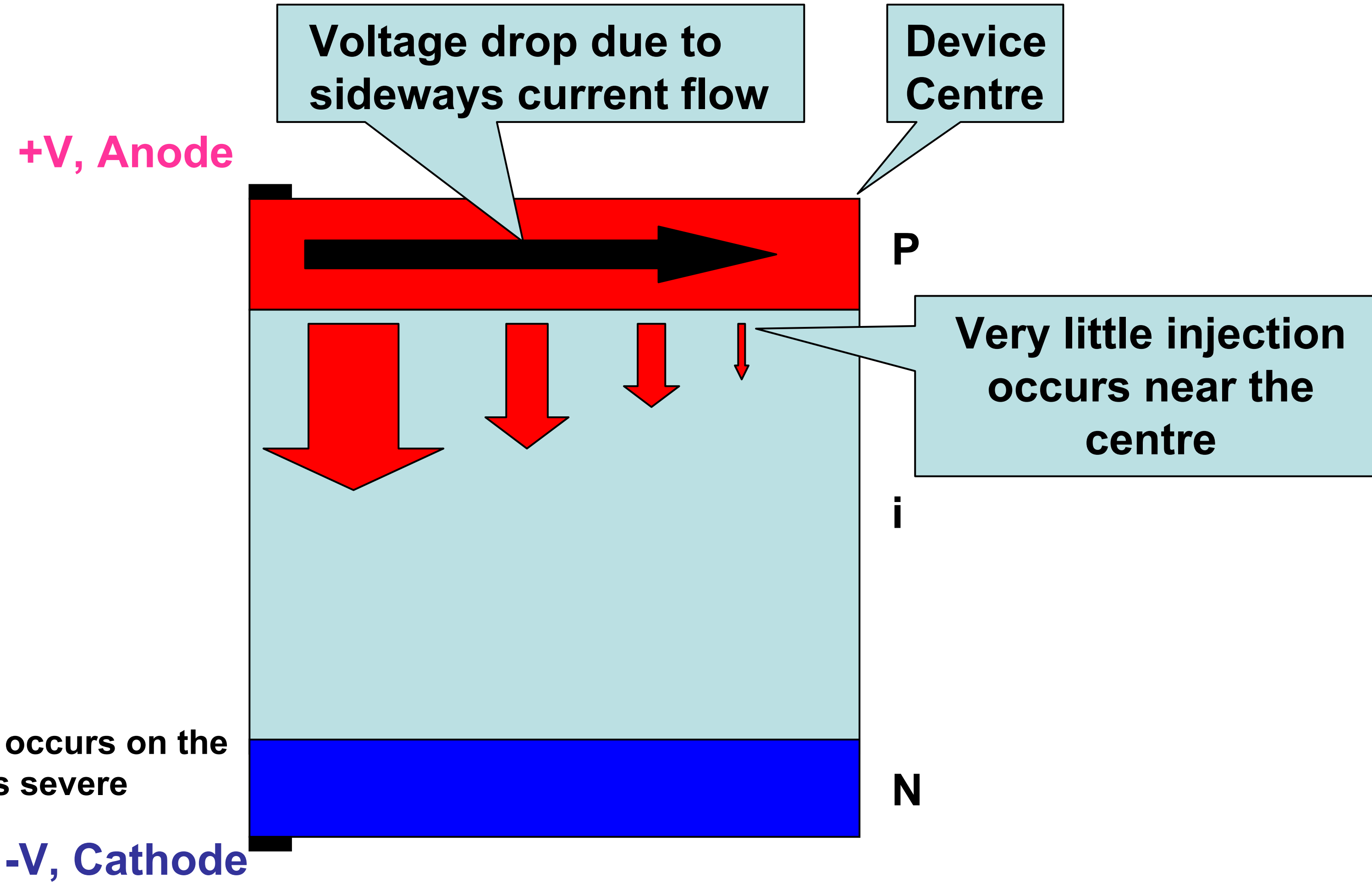
Design Criteria: Doping



$(N_p{*}x_p)$

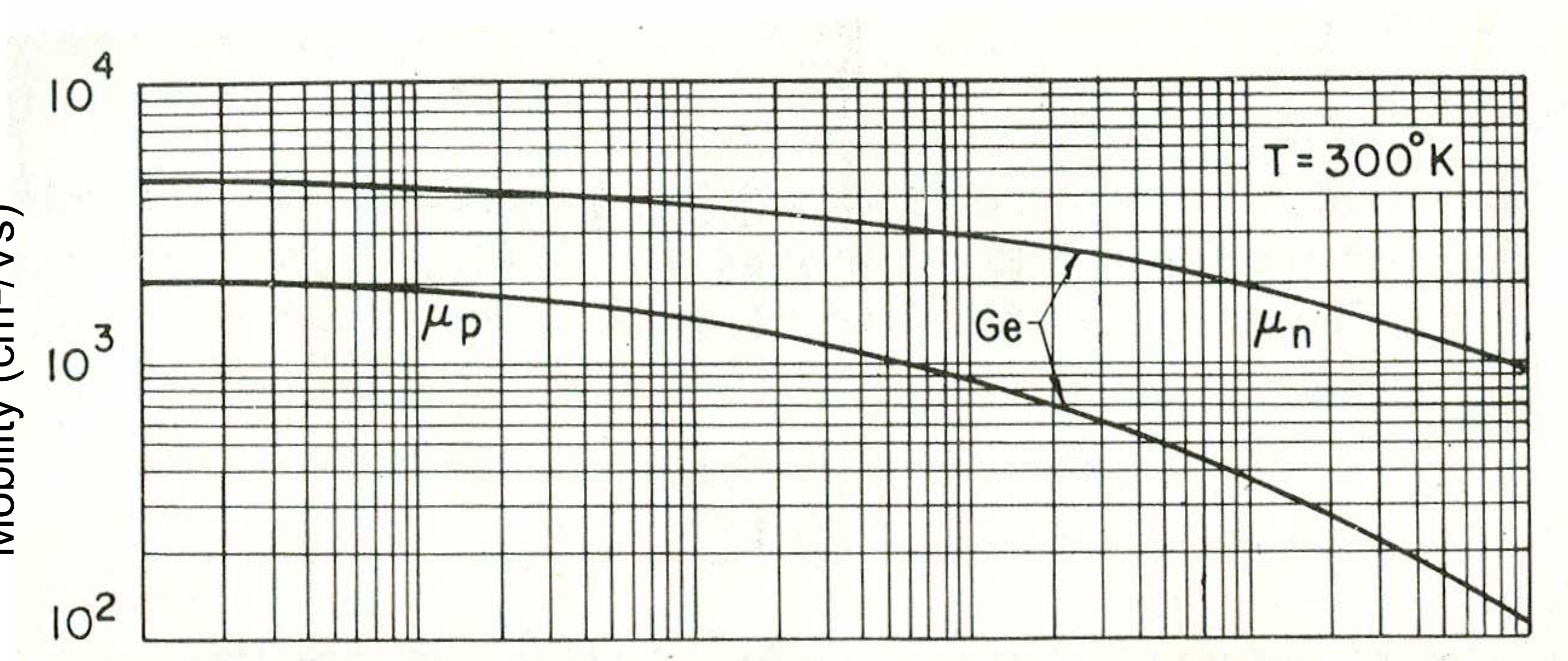
ON state: 95% transmission requires an area doping density of $\sim 1\times10^{14}$ /cm^2

Lateral Current Flow Problem



The problem also occurs on the N side, but is less severe

Carrier Mobility in Ge

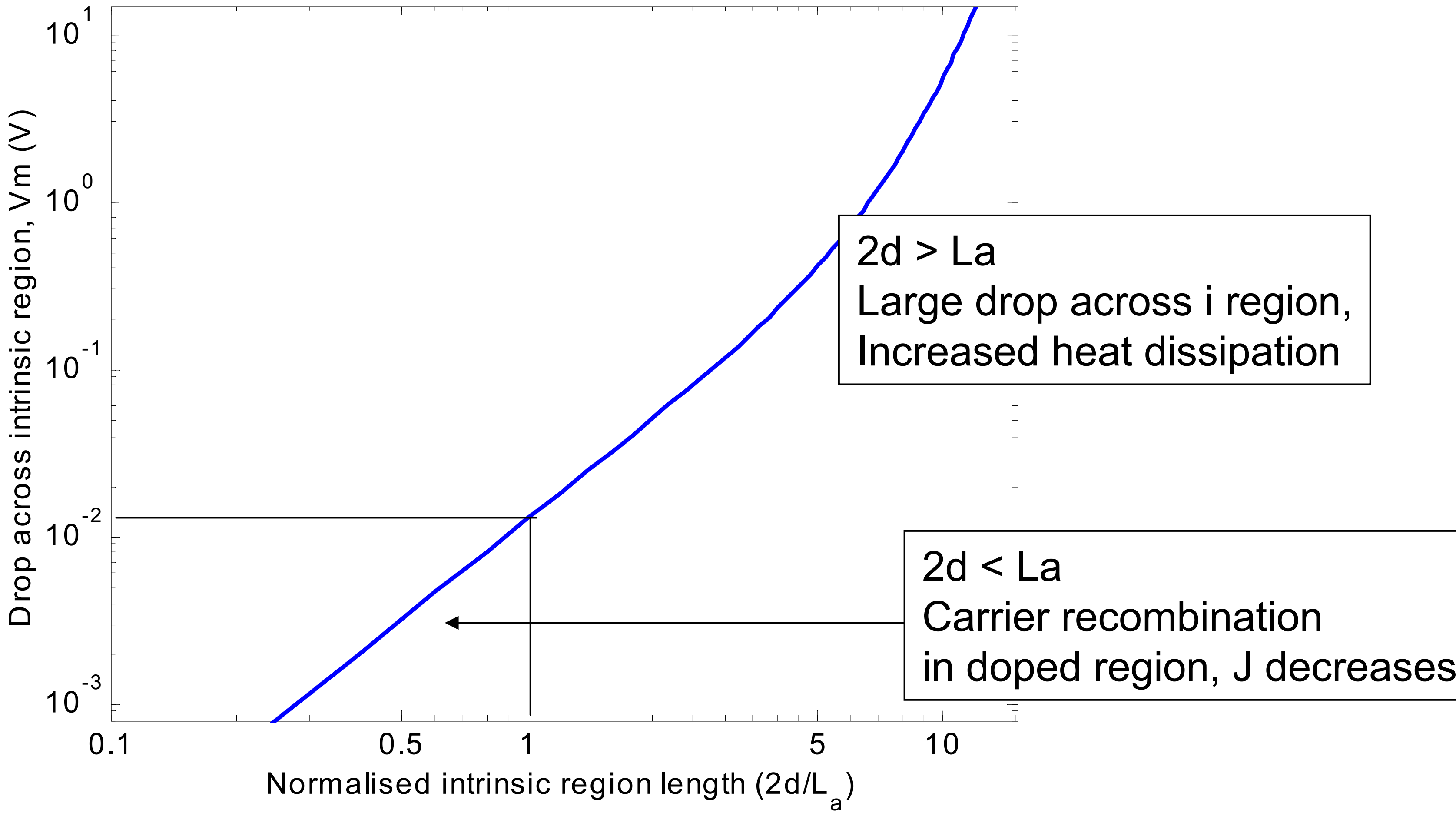


Mobility (cm²/Vs)

10^{14} Doping concentration (cm^{-3}) 10^{19}

We require high mobility for uniform current distribution!
Carrier-carrier scattering degrades mobility above ~ 1e15 /cm3

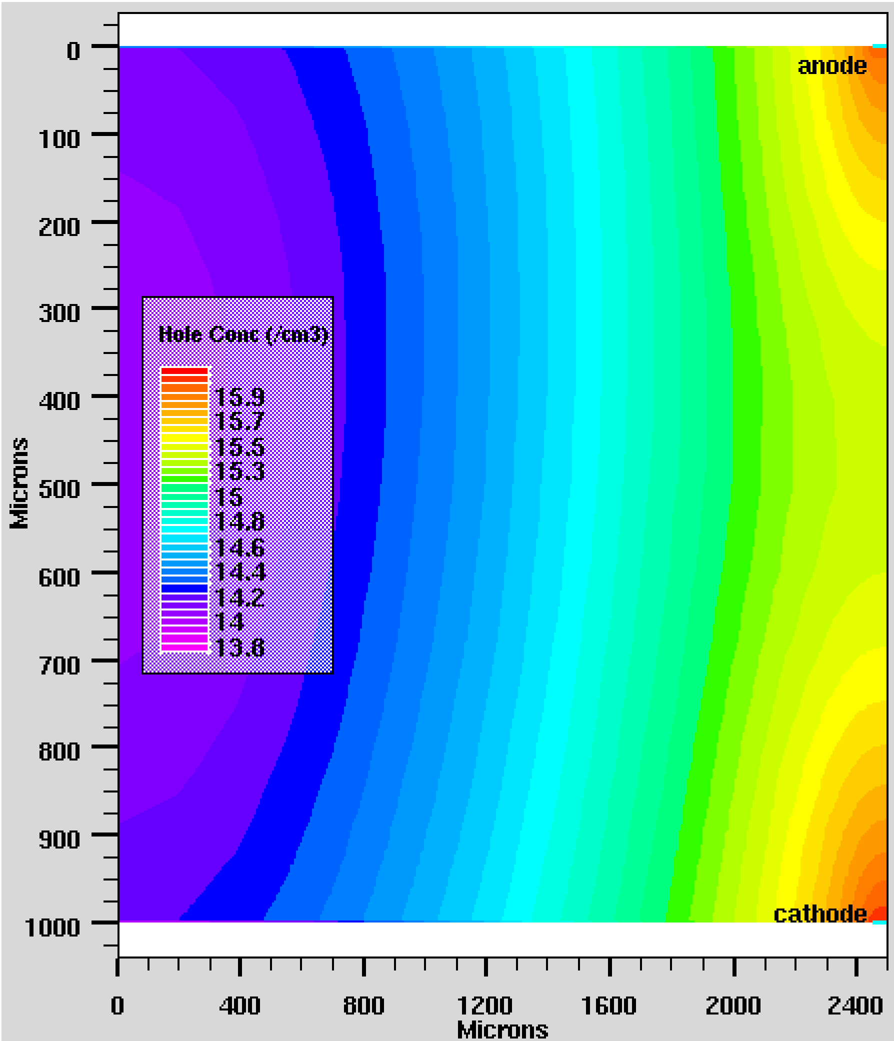
Drive voltage issues – intrinsic layer thickness



Simulations: ‘standard’ Ge

- 10µS lifetime, typical of ‘standard’ material
- 10^{18} /cm^{3} acceptors P side, 10^{14}/cm^{2}
- $5*10^{18}$ /cm^{3} donors N side, $5*10^{14}$/cm^{2}
- Gaussian profile
- Axisymmetric
- 50µm wide metal ring electrodes

Hole concentration at 0.6 Volts



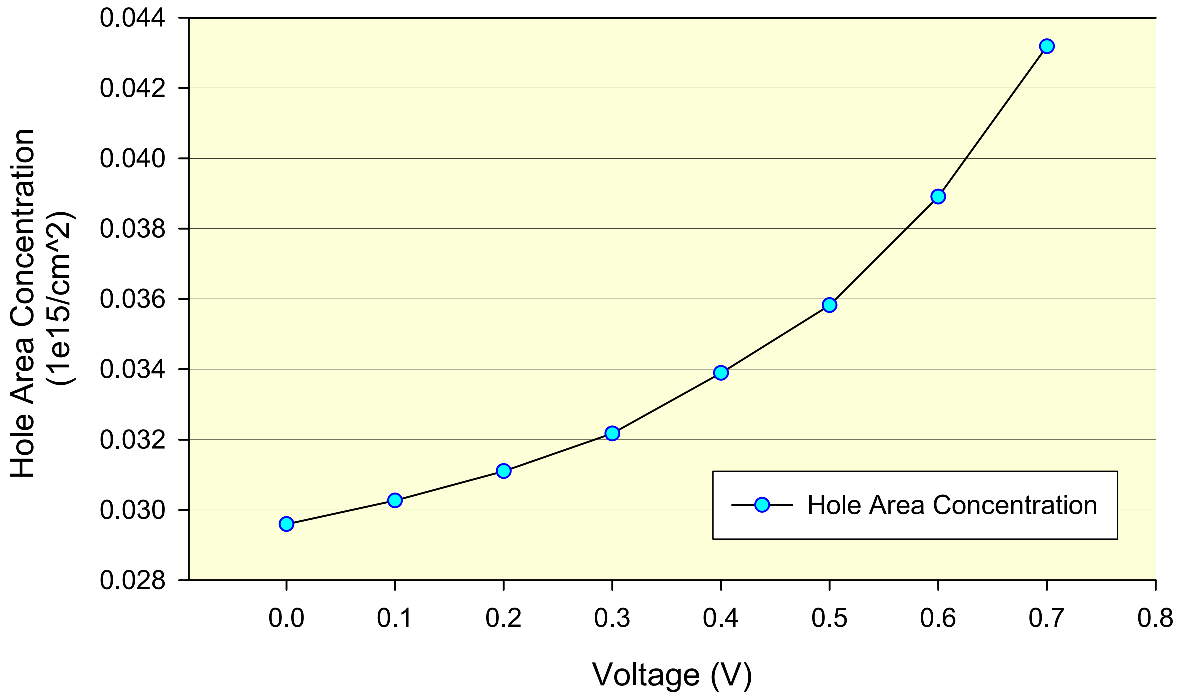
REMINDER!

We needed ~

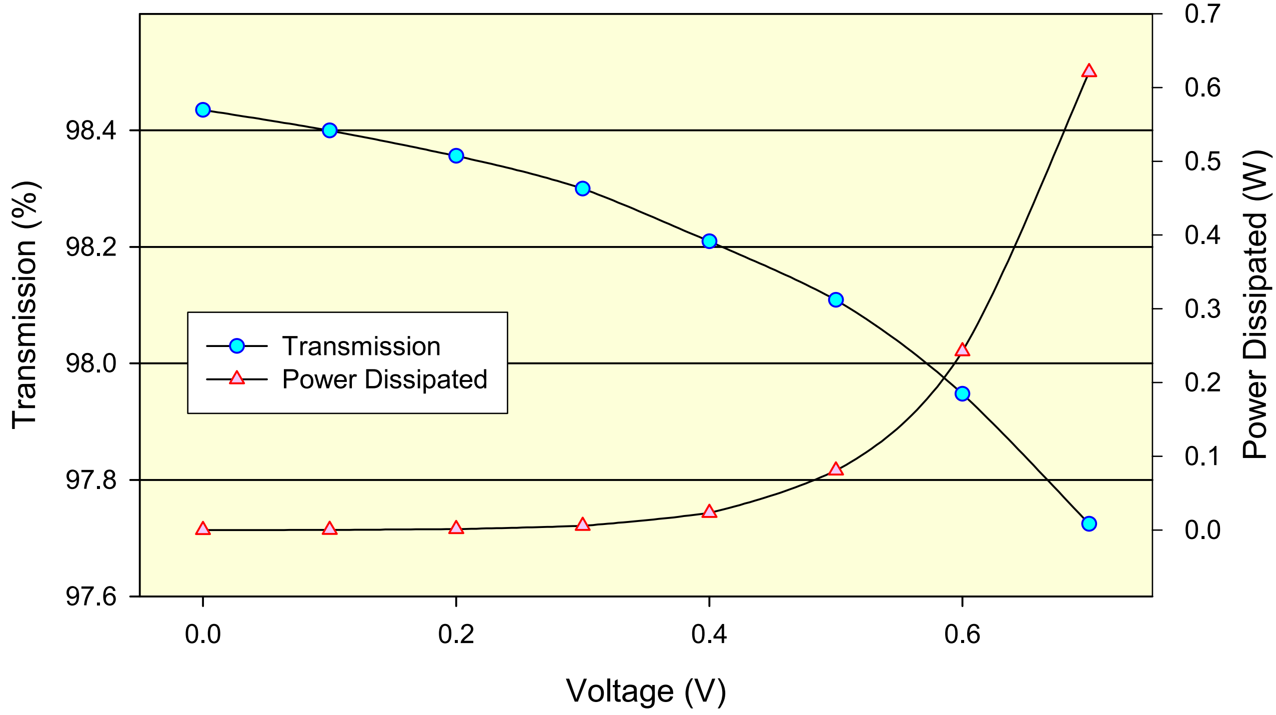
N_p=8.64*10^{16}/cm3

Oh dear……..

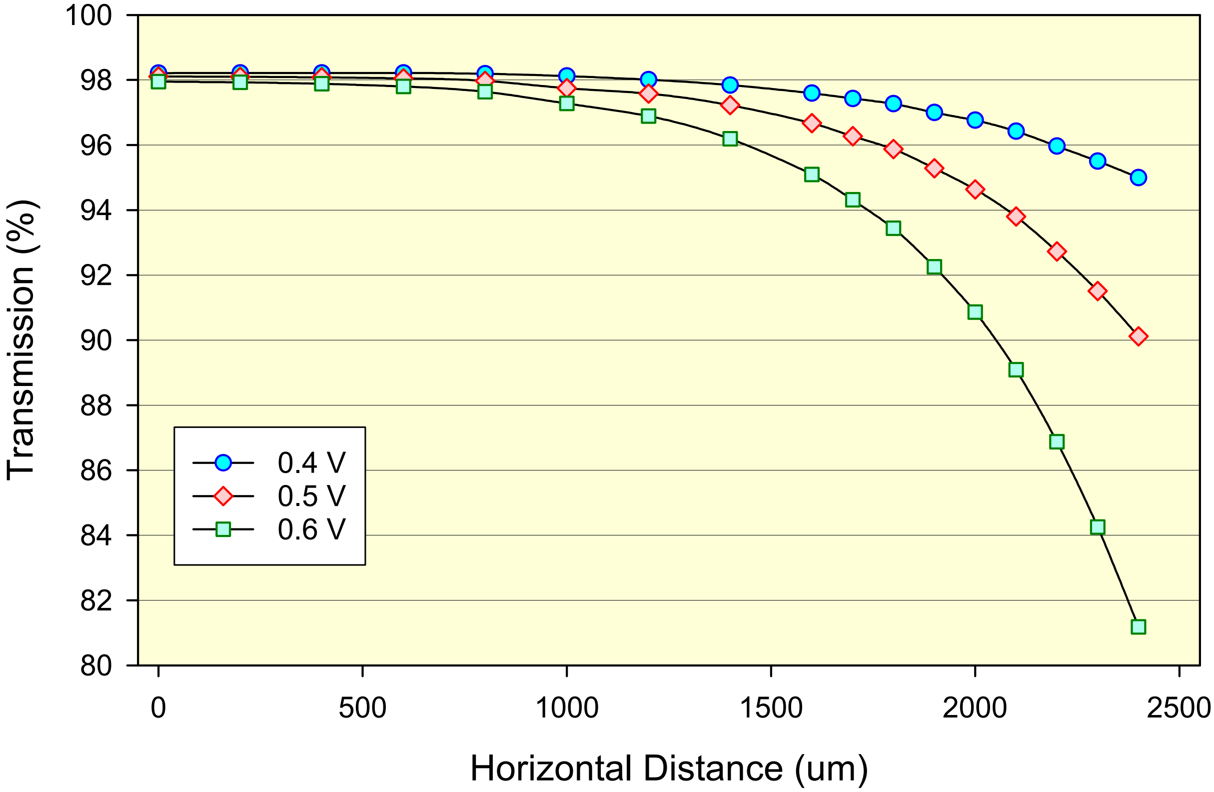
Central Hole Area Concentration as a fuction of Voltage (10us Tn and Tp)



Central Transmission through PiN Diode
(10us Tn and Tp)



Transmission through Diode vs Horizontal Distance (10us Tn and Tp)



Avoid Copper!

Copper has an ***EXTREMELY*** high SRH cross section!

Copper diffuses very rapidly through germanium

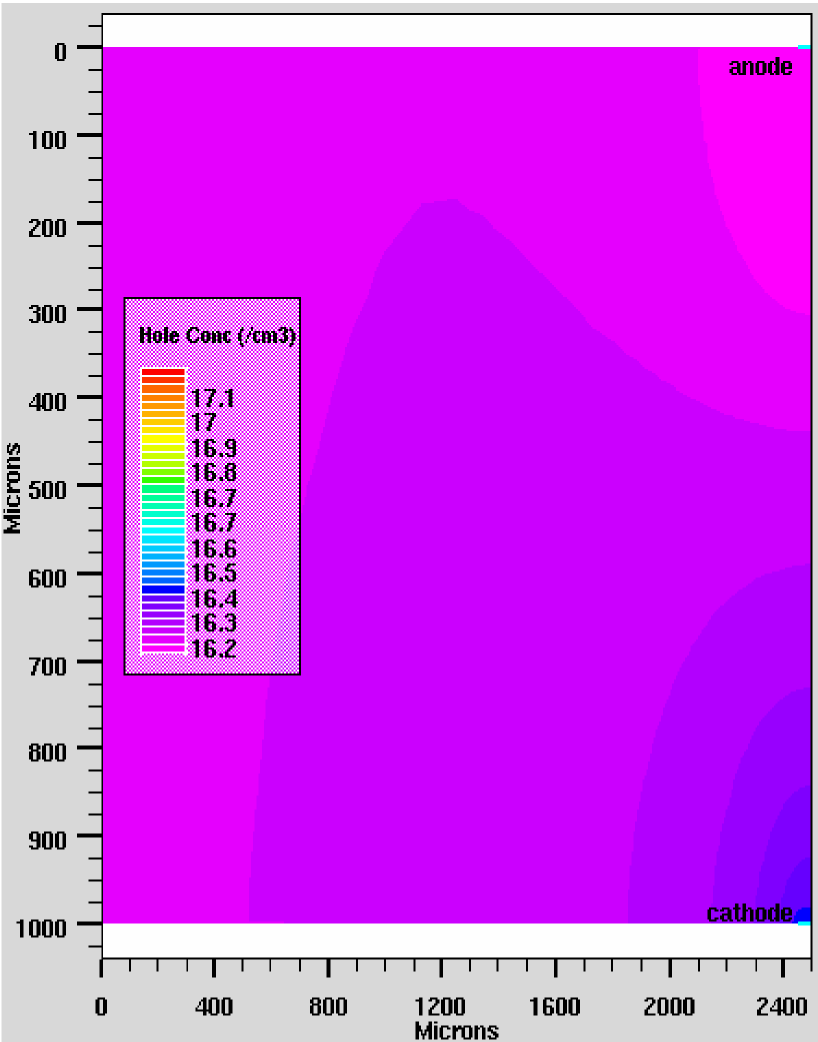
Tiny concentrations, ~10^{10}/cm3, severely shorten the lifetime.

Nuclear Detector is satisfactory, with lifetimes ~5mS

So we assume 2.5mS, allowing some processing loss

Avoidance of copper contamination is ***CRUCIAL***

Hole concentration at 0.4 Volts



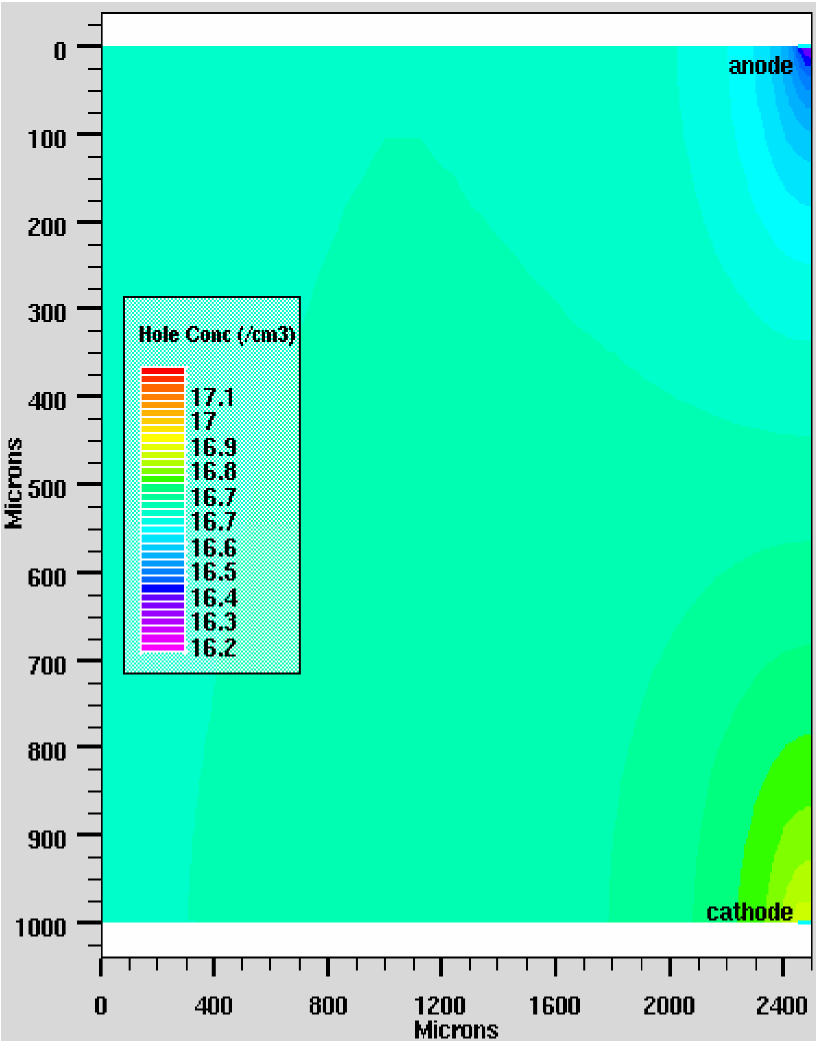
REMINDER!

We needed ~

$N_p = 8.64 * 10^{16}/cm3$

Hopeful…….

Hole concentration at 0.5 Volts



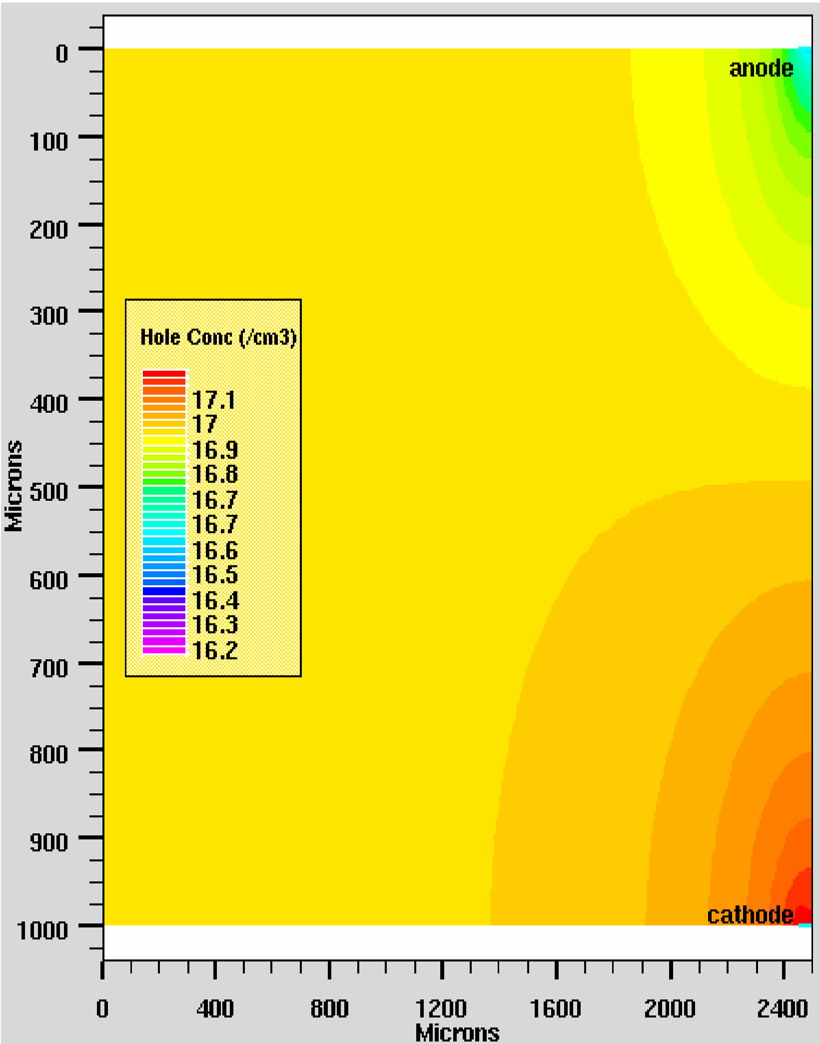
REMINDER!

We needed ~

N_p=8.64*10^{16}/cm3

Interesting……….

Hole concentration at 0.6 Volts



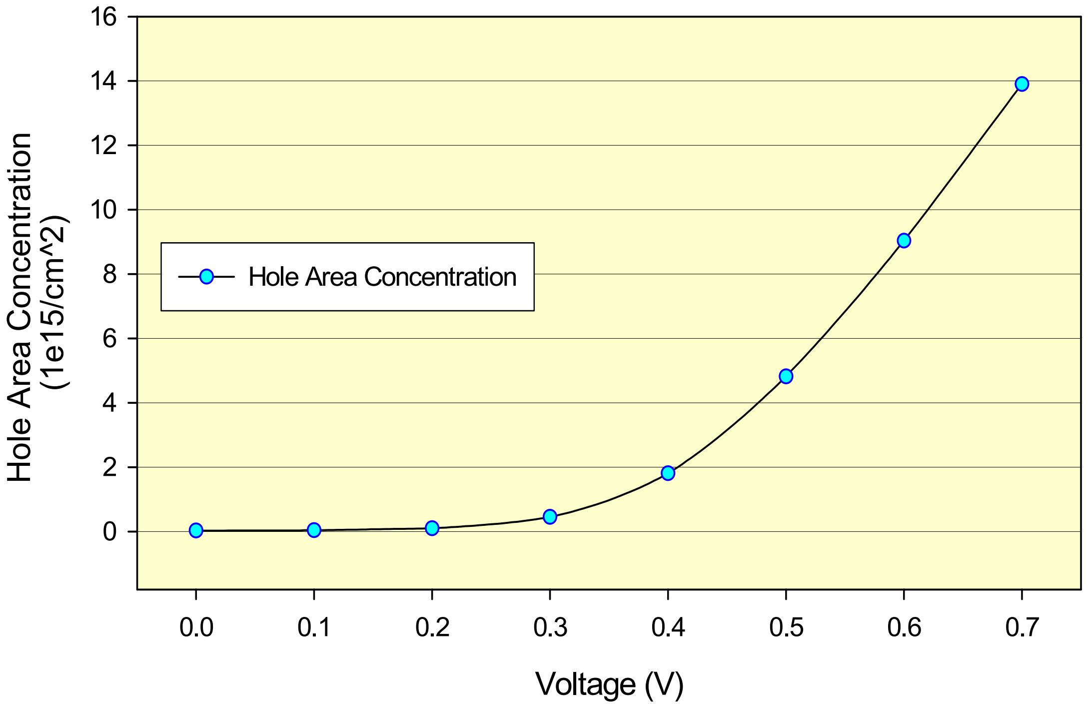
REMINDER!

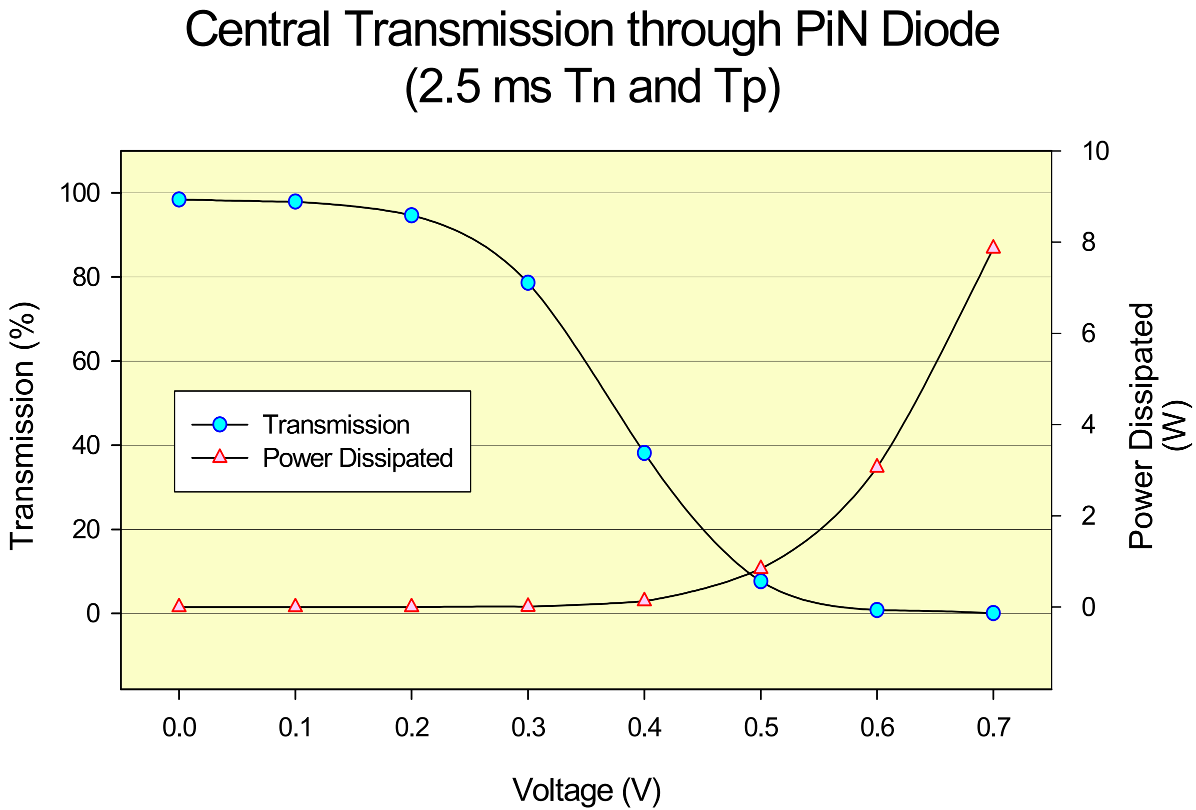
We needed ~

N_p=8.64*10^{16}/cm3

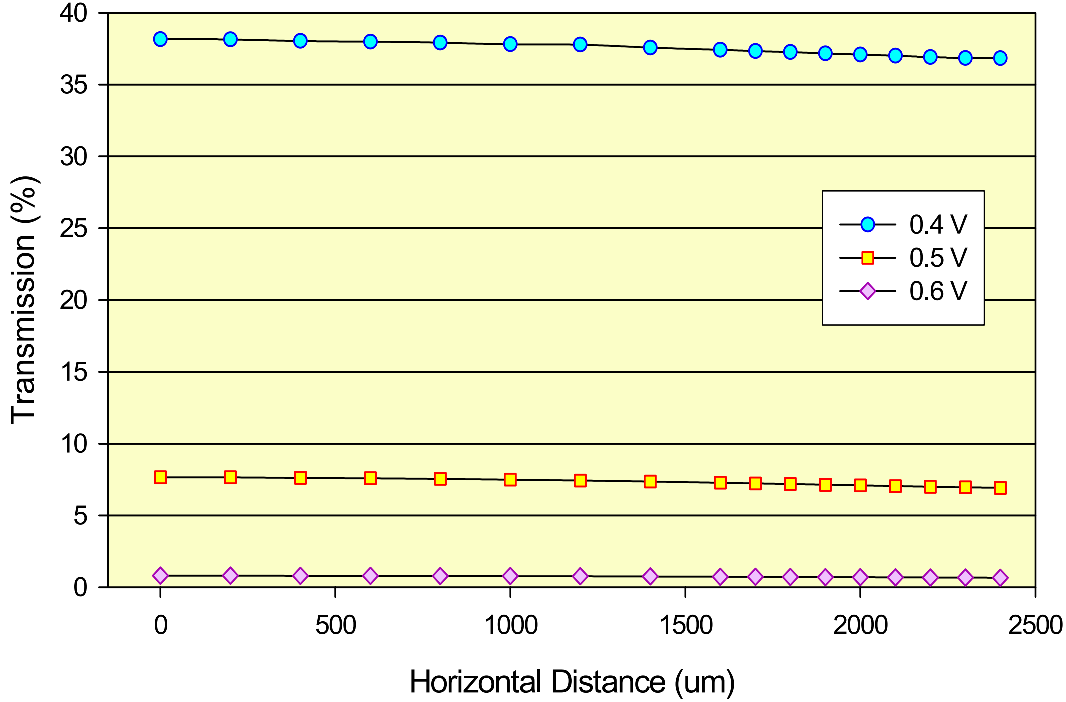
Whoopeeeeee…..

Central Hole Area Concentration as a function of Voltage (2.5 ms Tn and Tp)




Central Transmission through PiN Diode
(2.5 ms Tn and Tp)
Transmission (%)
Power Dissipated (W)
Voltage (V)
Transmission
Power Dissipated
100
80
60
40
20
0
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

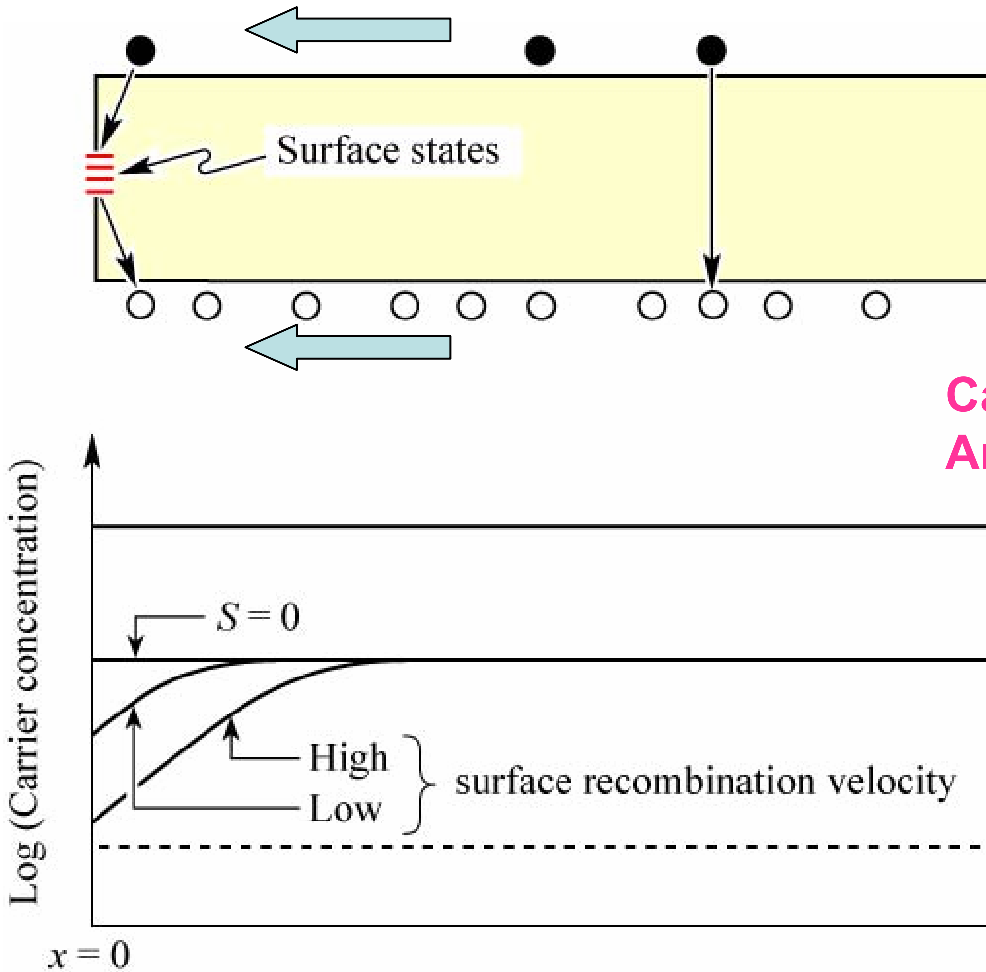
Transmission through Diode vs Horizontal Distance (2.5 ms Tn and Tp)



BUT…

- **There are issues…as always**
  - **Surface Recombination Velocity**
  - **Auger Recombination**
  - **Shockley-Read-Hall (SRH) Recombination**
  - Photon transitions (indirect band gap)
  - Impact ionisation (high E.Field only)
  - Tunneling (not possible)
  - Many-body effects on diffusivity

What is Surface Recombination?



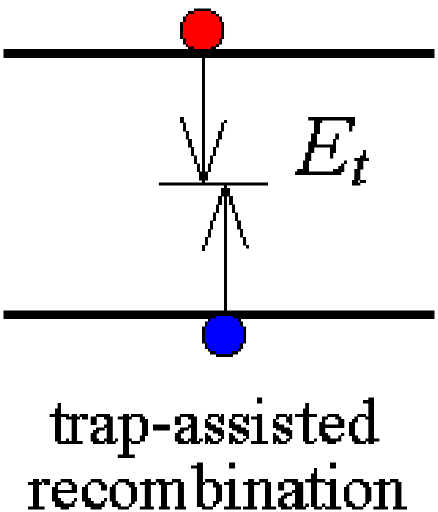
Conduction band

Valence band

Carriers diffuse to the surface And 'kill' the effective lifetime.

For Ge S=1-100cm/s

What is SRH Recombination



- Trap could be due to presence of foreign atoms such as Cu, Ni, Au or a structural defect in crystal
- The ultra-pure material is essential free of this
- But the heavily doped regions are damaged….

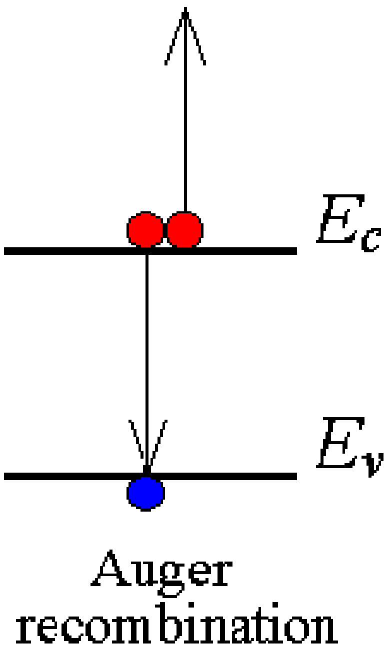
Concentration Dependent SRH

- No literature available on CONSRH in Ge, pure guess values!!

$$\tau_n = \frac{TAUN0}{1 + N/(NSRHN)}$$

- Quite Pessimistic values assumed, a factor of 1/10,000 i.e. from 10mS to 1 uS at highest concentration!
- The effect only operates over a very small volume of the device

What is Auger Recombination?



- Three particle effect

$$\partial n / \partial t = -\gamma_3 n^3.$$

- γ_3=1.1e-31 cm^6/s
- Some theoretical estimates lower (better)
- But not that well established at densities relevant to us.

Conclusions

- Some device modeling still needed for optimization
- Process simulation now more important
- Alloyed contacts may be used for fabrication?
- ***Lifetime preservation in processing absolutely crucial***
- ***The Auger parameter is a concern***
- ***But it does look possible***