Design Review #2: Resonant-Cavity Enhanced Photodetector (RCE-PD)

3.46 Photonic Materials and Devices

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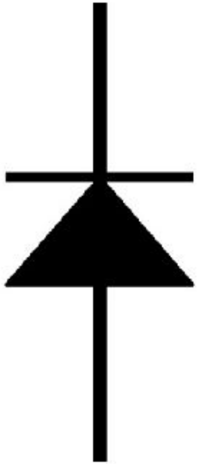
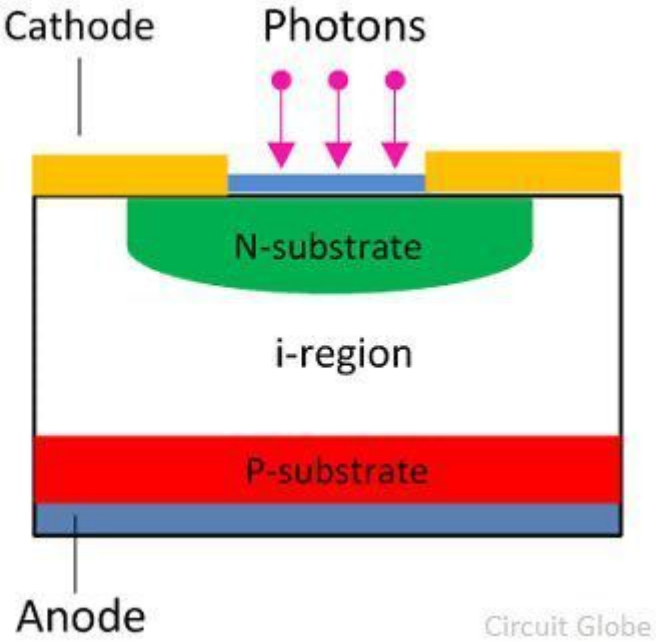
PIN Photodiode Fundamentals

Components:

- N-substrate
- I-region
    - Incident light → e-h pairs made → photocurrent
- P-substrate
- Cathode+Anode



Diode Equivalent Diagram



PIN Photodiode Diagram

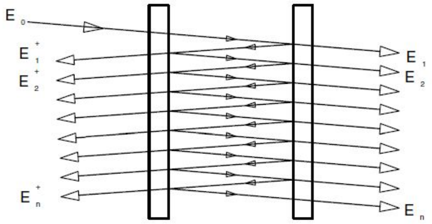
Resonant Cavity

Why?

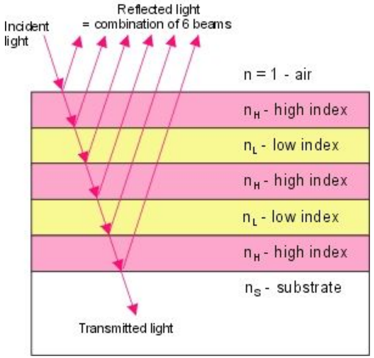
- Enhance absorption

How?

Use Distributed Bragg Reflectors (DBRs)



[Fabry-Perot cavity (INTERCONNECT) - Ansys Optics]



[Bragg Reflector Example]

Design Project RCE-PD Requirements

1. Stack height < 3[um]
2. 5[um] x 5[um] detector area
3. >50GHz 3dB Bandwidth
4. QE(lambda=850[nm]) > 50%
5. Optimized SNR

Refractive Indices (Cavity Layer)

__Hard Requirement__: intrinsic layer is Si

$$n_{cav}(\lambda = 850[nm]) = 3.6393 + j \cdot 0.0047757$$ Source, c-Si

Assume indecent angle is 0[rad]. Resonant cavity length:

$$d = \frac{m\lambda}{2Re\{n\}}$$

Length cost per m: 116.8[nm]

P-N Features

From internet, doping level is appropriate at ~1e18[cm-3]

- P: Na = 1e18 [cm-3]
- N: Nd = 1e18 [cm-3]

From internet, thickness of ~75[nm] is acceptable

Thus,...

$$d_i = d_{cav} - 2 * 75[nm]$$

3dB bandwidth

<u>Two Restraints:</u>

1. Carrier-transport time limit $$f_{tr} = \frac{0.44 v_{sat}}{d}$$
2. RC delay $$f_{RC} = \frac{1}{2\pi RC} \sim \frac{d}{2\pi R \varepsilon A}$$

Considering Both…

$$f_{3dB} = \sqrt{\frac{1}{(1/f_{tr})^2 + (1/f_{RC})^2}}$$

Detector Area

Locks A to 25[um^2], setting f_{RC}

$$f_{RC} = \frac{1}{2\pi RC} \sim \frac{d}{2\pi R \varepsilon A}$$

Also means front DBR <u>must</u> be 5[um] x [5um]

50GHz 3dB Requirement

Looking at the entire 3dB formula…

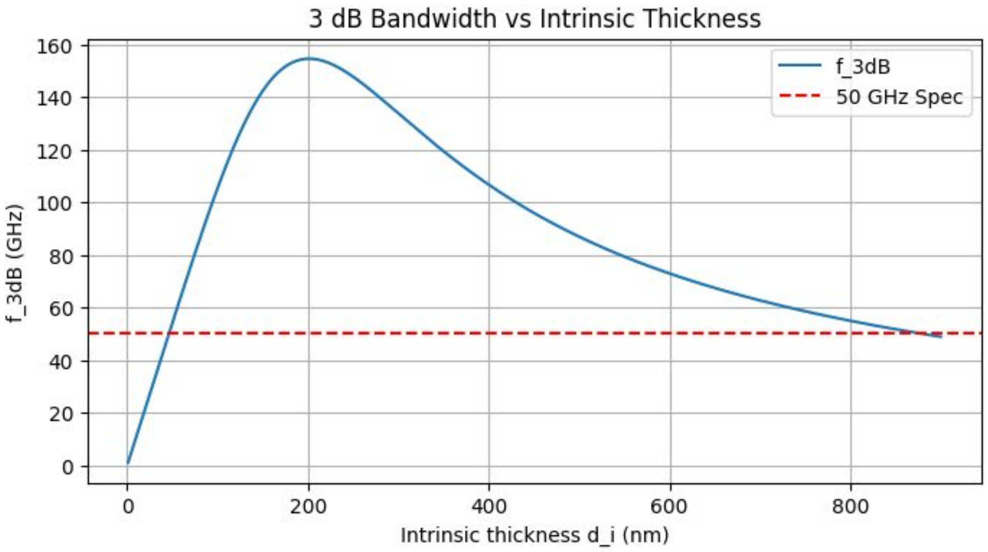
$$f_{3dB} = \sqrt{\frac{1}{(1/f_{tr})^2 + (1/f_{RC})^2}}$$

f_{RC} known (last slide)

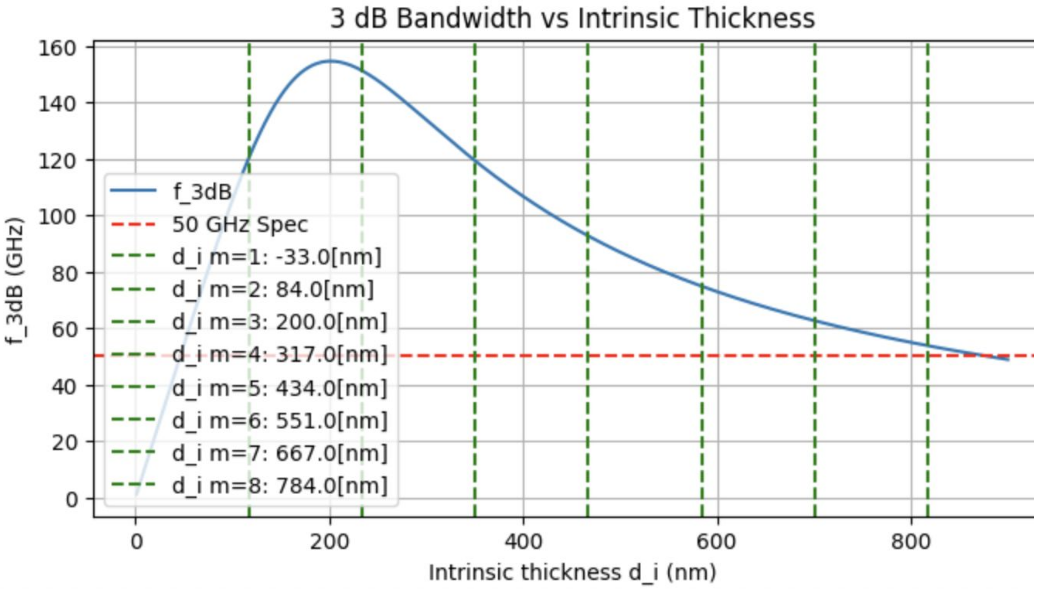
$$f_{tr} = \frac{0.44 v_{sat}}{d}$$

For Si, $v_{sat} = 1 \cdot 10^5 [m/s]$

Graph as a function of d (left)



Intrinsic Layer Thickness Restrained by Cavity



We can safely use m=2 to m=8

Refractive Indices (Distributed Bragg Reflectors)

DBR requirements:

1. High index difference (high reflection with less thickness)
2. Almost lossless at 850[nm] wavelength

Solution: GaP + SiO2

GaP onto SiO2: MetalOrganic Vapor Phase Epitaxy (MOVPE)
Implementation paper

GaP onto Si: Wafer Bonding
Implementation paper

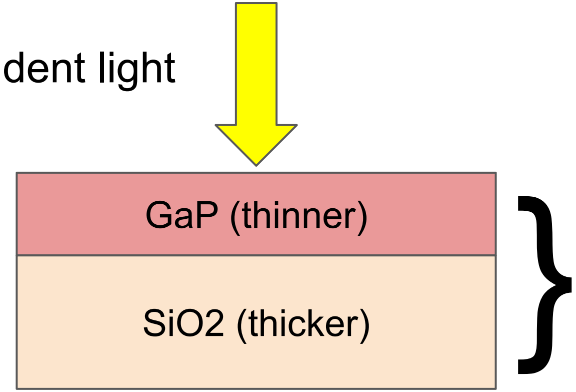
At wavelength=850[nm]...

$n_{SiO2} = 1.4525$ source $n_{GaP} = 3.1621$ source

Constructing a Bragg Mirror

$$d_{GaP} = \frac{\lambda_0}{4n_{GaP}} = 67.2[nm]$$

$$d_{SiO2} = \frac{\lambda_0}{4n_{SiO2}} = 146.3[nm]$$



Length cost per layer: 213.5[nm]

Bottom DBR

From literature, bottom DBR usually reflects >99.9%

Determine N using TMM matrix method

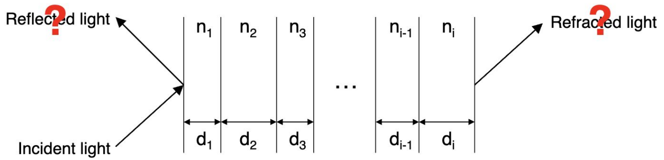
- Assume TE, angle of incidence is 0[rad]

Interface matrix (TE):

$$D_{TE} = \frac{1}{2}\begin{bmatrix} 1+\frac{n_t\cos\theta_t}{n_i\cos\theta_i} & 1-\frac{n_t\cos\theta_t}{n_i\cos\theta_i} \\ 1-\frac{n_t\cos\theta_t}{n_i\cos\theta_i} & 1+\frac{n_t\cos\theta_t}{n_i\cos\theta_i} \end{bmatrix}$$

Propagation matrix

$$P_i = \begin{bmatrix} \exp(-ik_{i,z}d_i) & 0 \\ 0 & \exp(ik_{i,z}d_i) \end{bmatrix}$$



Transfer matrix $M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = D_{01}\cdot P_1 \cdot D_{12}\cdot P_2 \cdot \ldots \cdot P_i \cdot D_{i,i+1}$

$$\begin{pmatrix} E_i \\ E_r \end{pmatrix} = M \begin{pmatrix} E_t \\ 0 \end{pmatrix} \Rightarrow \begin{cases} \text{Transmittance: } T = \frac{|E_t|^2}{|E_i|^2} = \frac{1}{|M_{11}|^2} \\ \text{Reflectance: } R = \frac{|E_r|^2}{|E_i|^2} = \left|\frac{M_{21}}{M_{11}}\right|^2 \end{cases}$$

Post-simulation: N=7

Length cost for bottom DBR: 1.50[um]

Top DBR

Absorbed power:

$$R + T + A = 1$$

Where,...

$R \rightarrow$ Reflectance

$T \rightarrow$ Transmittance

$A \rightarrow$ Absorbance

Can solve for A with TMM of entire stack

Varying N with fixed bottom DBR, max absorption at N=3

Use on M for entire stack:

$$T = \frac{|E_t|^2}{|E_i|^2} = \frac{1}{|M_{11}|^2}$$

$$R = \frac{|E_r|^2}{|E_i|^2} = \left|\frac{M_{21}}{M_{11}}\right|^2$$

Length cost for top DBR: 0.64[um]

Finalizing Cavity Thickness

In general, thicker intrinsic region gives higher absorption

Looking at m=5…

- TMM absorption = 93.9%
- TMM reflection = 6%
- Length = 5*116.8[nm]=584[nm]

Total Length: 2.719[um] (satisfied!)
Intrinsic Thickness: 434[nm]

Determining Quantum Efficiency

No “direct” formula for photocurrent generation (Python not enough)

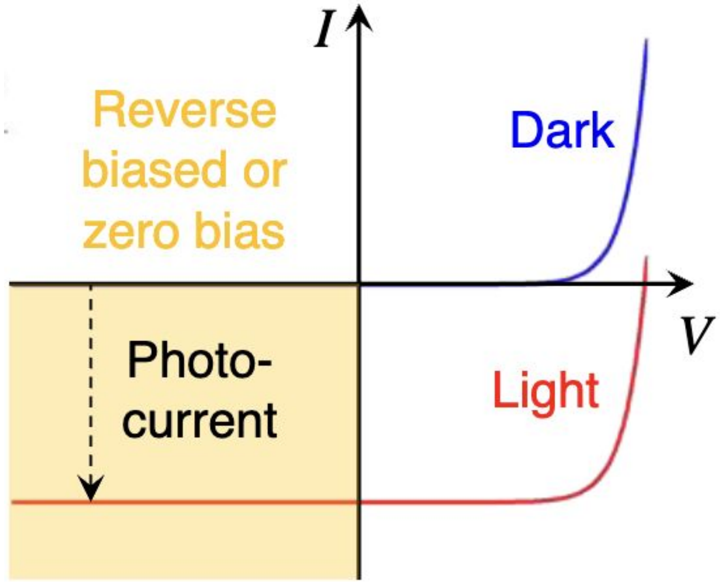
Use SimWindows to measure:

- Dark Current
- Photocurrent
- Absorption

<u>PROBLEM</u>: SimWindows does not model TMM (cannot simulate full RCE-PD)

To simulate, also need a reverse bias voltage

- Set to -3V



Carrier Collection Efficiency

<u>SOLUTION:</u> get carrier collection efficiency (ζ) of Si PIN setup

$$\eta(\lambda)=\left[1-R_{\lambda}(\lambda)\right]\cdot\zeta\cdot\left[1-e^{-\alpha(\lambda)d}\right]$$

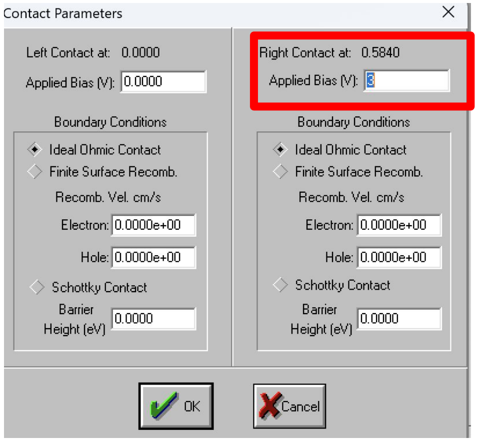
ζ constant in setup, so we can apply this constant to the TMM model

Current Simulation Inputs:

```
grid length=0.584 points=2500

structure material=si length=0.584

doping length=0.075 Na=1e18
doping length=0.434
doping length=0.075 Nd=1e18
```



Measurements

$$\eta(\lambda) = \left[1 - R_\lambda(\lambda)\right] \cdot \zeta \cdot \left[1 - e^{-\alpha(\lambda)d}\right]$$

$\left[1 - R_\lambda(\lambda)\right]$: Start Simulation in intrinsic layer (term goes to 1)

$\left[1 - e^{-\alpha(\lambda)d}\right]$: Plot “Total Poynting [mW/cm2]”, calculate manually (~0.0334)

For Responsivity… $\mathbf{R} = \frac{I_{photocurrent} - I_{dark}}{P_{in}} = \eta \cdot \frac{\lambda}{1.24}$

Power input: 100[mW/cm2]
Photocurrent at power input: 2.287*10**(-3) [A/cm2]
Dark Counts: 8.05*10**(-16) [A/cm2] *(<u>very</u> negligible)*

Relate **R** to ζ: <u>ζ~99.8%</u>

$$\zeta = \frac{\mathbf{R} \cdot 1.24}{\lambda \cdot \left[1 - e^{-a(\lambda)d}\right]}$$

Quantum Efficiency Calculation

$$\eta(\lambda) = \left[1 - R_\lambda(\lambda)\right] \cdot \zeta \cdot \left[1 - e^{-\alpha(\lambda)d}\right]$$

$\left[1 - R_\lambda(\lambda)\right]$: TMM reflection (6%)

$\left[1 - e^{-\alpha(\lambda)d}\right]$: TMM absorption (93.9%)

Quantum Efficiency: 88%

Quantum Bit Error Rate (qBER)

Wanted qBER parameters:

- 50Gbps
- qBER > 10**(-9) requested

Probability of received photons ***m*** given expected photons $\overline{m}$:

$$P(m) = \left(\overline{m}\right)^m \cdot \exp\left(-\overline{m}\right) / m!$$

Need to define:

- Expected photons
- Threshold for 0/1 distinguishing (base on dark current)

BER Calculation Method

From slides,... $\mathrm{BER} = \frac{1}{2}(P_0 + P_1)$

- P0 = probability of detecting 0 as a 1
- P1 = probability of detecting 1 as 0

P0 VERY small from measured dark current, threshold=1 works

$$P_0 = 1 - \frac{\bar{m}_{dark}^0 exp(-\bar{m}_{dark})}{0!} \qquad \bar{m}_{\textbf{dark}} = \frac{i_{\textbf{dark}} t_b}{q}$$

$$P_1 = \frac{\bar{m}_I^0 exp(-\bar{m}_I)}{0!} \qquad \bar{m}_I = \frac{\eta P \lambda_0}{hc \cdot \textbf{bps}}$$

Varying power P,...

P=2.89e-7[W] → 1156[mW/cm2] needed to reach BER requirement

SNR Considerations

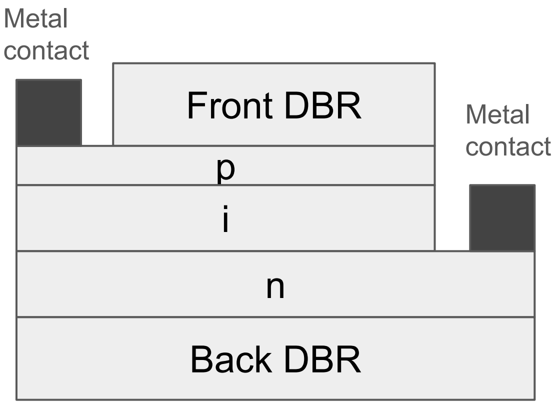
Assuming we operate at the power and bandwidth specified previously, define SNR as…

$$SNR = \left(\frac{\bar{i}}{\sigma_i} \right)^2$$

Using $\sigma_i^{\ 2} = 2e \cdot \bar{i} \cdot B$, $B \sim \frac{1}{2\tau_{int}}$, and $\bar{i} = \eta \cdot \frac{0.85}{1.24} P$, we get shot noise SNR=20dB obtained

Dark current contributes VERY little to shot noise

Final “Spec Sheet”



(not to scale)

Thickness: 2.7[um]
QE: 88%
f_3dB: 95[GHz]
Front DBR: 5um x 5um (light-receiving area)
Power for BER at 10e-9: 2.89e-7[W]
SNR at BER Power: 20dB
Reverse bias: -3[V]

Closing Thoughts

Improvements?

Cavity length could be increased

- Leeway with vertical stack thickness (I had 0.3[um] left)
- Still achieved req’s, but could have been better…

Resistivity considerations

Use of AI:

- Early stages: finding relevant papers and articles on RCE-PDs
- Middle stages: Double-checking code, some erroneous assumptions
- End stages: Seeing if my values “made sense,” not very helpful…