Resonant Cavity Enhanced Photodetector

3.46 Photonic Materials and Devices

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***Abstract*—This paper walks through the design and analysis a silicon resonant-cavity-enhanced (RCE) photodetector operating at 850 nm that achieves >50% quantum efficiency and >50 GHz 3dB bandwidth within a 5 µm × 5 µm active area and a total device thickness below 3 µm. Resonant field enhancement provided by a Fabry–Pérot cavity formed by distributed Bragg reflectors enables high absorption in a thin intrinsic region, overcoming the bandwidth–responsivity trade-off of conventional silicon PIN photodiodes. Device performance is optimized using transfer-matrix-method modeling and semiconductor simulations.**

I. Problem Statement

As optical technologies advance, the demand for photodetectors that combine high sensitivity with high-speed operation has grown significantly. In recent years, AI companies have shown interest in photonic devices to enhance compute times. A common photodetector architecture is the PIN photodiode, which consists of an intrinsic region sandwiched between doped p- and n-type layers. When operated under reverse bias and given an optical input, the intrinsic region generates a photocurrent.

One challenge in engineering a high-responsivity and high-bandwidth device is the competing restraints on the intrinsic layer thickness. Increasing this parameter improves optical absorption and thus quantum efficiency, but at the cost of device bandwidth.

Resonant-cavity-enhanced (RCE) photodetectors overcome this limitation by embedding the absorbing region inside a Fabry–Pérot resonator formed by two distributed Bragg reflectors (DBRs). At the cavity resonance, the standing-wave field inside the cavity is amplified, greatly increasing the effective absorption without increasing the physical thickness. This allows RCE photodiodes to achieve high quantum efficiency while maintaining a thin i-layer, thereby preserving device bandwidth.

In this work, the design and analysis of an RCE photodetector is investigated, with particular design requirements listed below:

- *operating wavelength at* $\lambda = 850[nm]$
- *active region composed of silicon (Si)*
- *photodetector stack height* $< 3[\mu m]$
- $5[\mu m] \times 5[\mu m]$ *detector area*
- $> 50[GHz]$ *3dB-bandwidth*
- *Quantum Efficiency* $> 50\%$
- *Optimized SNR*

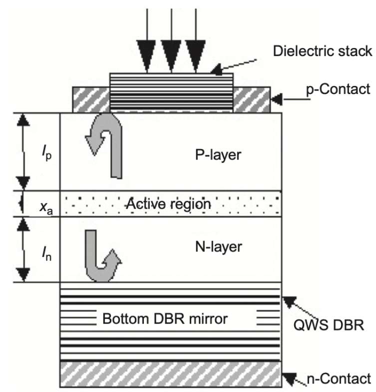

Fig. 1: Example RCE-Photodetector Structure [5]

To achieve these goals, I optimized mirror reflectivities, cavity mode support, intrinsic-layer thickness, and overall absorption using a transfer-matrix-method (TMM) model and a semiconductor device simulation.

II. Design & Analysis

The design of this device will be broken into relevant sections of optimization.

A. 3dB Bandwidth

To determine the 3dB device bandwidth, we must consider the effects of carrier-transport time and RC delay.

The carrier-transport time arises from the velocity at which photogenerated carriers traverse the intrinsic region. Its contribution can be expressed as:

$$f_{tr} = \frac{0.44 v_{sat}}{d_{intrinsic}} \tag{1}$$

where v_{sat} is the saturation velocity and $d_{intrinsic}$ is the intrinsic region thickness. Silicon is used in the active region, giving $v_{sat} = 1 \cdot 10^5[m/s]$. Thus, f_{tr} can be expressed as a function of intrinsic layer thickness.

The RC delay accounts for the load resistance and the effective capacitance formed by the PIN junction. Approximating our setup as a perfect parallel-plate capacitor, we can express capacitance as $C = \frac{\varepsilon A}{d}$ and express the RC delay as:

$$f_{RC} = \frac{1}{2\pi RC} \approx \frac{d_{intrinsic}}{2\pi R \varepsilon A} \tag{2}$$

where R is the load resistance (by convention, $50[\Omega]$), ε is the permittivity of the dielectric (based on Si), and A is the parallel-plate area. The design is restrained to a $5[\mu m] \times 5[\mu m]$ detection area, so $A = 25[\mu m]^2$. Thus, f_{RC} can be expressed as a function of $d_{intrinsic}$.

Combining the effects of these restraints, we arrive at a 3dB device bandwidth formula (Eq. 3):

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

Because I expressed f_{tr} and f_{RC} as functions of variable parameter $d_{intrinsic}$, a range of valid $d_{intrinsic}$ where $f_{3dB} > 50[GHz]$ can be determined. Fig. 2 demonstrates this result:

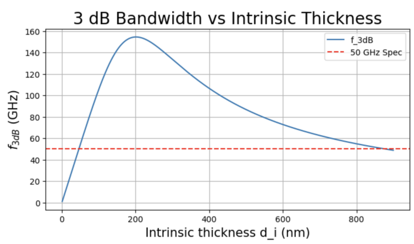

Fig. 2: 3dB bandwidth (GHz) vs intrinsic thickness (nm). Red line represents 50[GHz]

The plot shows that, to achieve $f_{3dB} > 50[GHz]$, the intrinsic thickness must be in the range $70[nm] < d_{intrinsic} < 850[nm]$. The intrinsic thickness will not be hard-set for now, but this range will be accounted for in the final length.

B. Distributed Bragg Reflectors (DBRs)

Bragg mirrors are designed by repeatedly-stacking a high-index and low-index dielectric layer. Increasing the number of layers increases the reflectivity of the setup. Assuming an incidence of 0 rad, the length of each dielectric is given by:

$$d_{\lambda/4} = \frac{\lambda}{4n} \tag{4}$$

where λ is the operating wavelength and n is the refractive index of the material layer.

When searching for materials to construct the Bragg reflectors, a special emphasis was placed on materials with a high index contrast. A higher index contrast implies less dielectric layers are needed for high reflectivities, promising a reduced thickness cost. Emphasis was also placed on low or negligible absorption at the operating wavelength ($\lambda = 850[nm]$), as absorption would interfere with optimal mirror reflectivity. Upon research, Silicon Dioxide (SiO_2) and Gallium Phosphide (GaP) fulfilled these desires. Their refractive indices at $\lambda = 850[nm]$ [2] are demonstrated in (Eq. 5) and (Eq. 6) respectively:

$$n_{SiO2} = 1.4525 \tag{5}$$

$$n_{GaP} = 3.1621 \tag{6}$$

It should be noted that, because GaP has a crystalline structure and SiO_2 is an amorphous structure, growing these materials on each other is a non-trivial task. One solution would be to generate crystalline SiO_2, though this method proves tricky and expensive. An alternative method is to utilize a thin Al_2O_3 wafer to connect the materials [1]. For the purposes of this paper, I will assume that the growth method does not interfere with our calculations and is feasible.

To calculate the reflectivity inside the cavity, I used the Transfer Matrix Method (TMM). Given the refractive indices, propagation lengths, incidence angles and refracted angles, we can calculate a matrix M that describes the wave evolution through a system.

We define a wave's evolution through a system by considering the total incident (E_i), reflected (E_r), and transmitted (E_t) electric fields:

$$\begin{pmatrix} E_i \\ E_r \end{pmatrix} = M \begin{pmatrix} E_t \\ 0 \end{pmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{pmatrix} E_t \\ 0 \end{pmatrix} \tag{7}$$

Fig. 3 demonstrates the construction of the M matrix, using $D_{i,i+1}$ to describe the interface between two dielectrics and P_i to describe the phase evolution in space. The matrices are multiplied from order of light interaction.

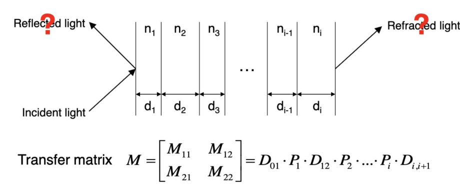

Fig. 3: Diagram of TMM Analysis [3.46 Lecture Notes]

Assuming an angle of incidence $\theta_i = 0[rad]$ and a strict use of TE-polarized light, the interface matrix D_{TE} can be represented as:

$$D_{TE} = \frac{1}{2} \begin{bmatrix} 1 + \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} & 1 - \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} \\ 1 - \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} & 1 + \frac{n_t cos(\theta_t)}{n_i cos(\theta_i)} \end{bmatrix} \tag{8}$$

and the propagation matrix P_i can be represented as:

$$P_i = \begin{bmatrix} e^{-ik_{i,z}d_i} & 0 \\ 0 & e^{+ik_{i,z}d_i} \end{bmatrix} \tag{9}$$

After obtaining the matrix M, the total reflectance R and transmittance T can be calculated using (Eq. 10) and (Eq. 11) respectively:

$$R = |\frac{M_{21}}{M_{11}}|^2 \tag{10}$$

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

From various selections of literature [3], [5] , the bottom DBR should be optimized for high-reflectance. By stacking the GaP/SiO_2 structure N times, $R > 99.9\%$ is achieved. Fig 4 demonstrates a schematic of the DBR. Running a Python program with the calculated TMM for the DBR, we find that $N_{bottom} = 7$ satisfies the desired R

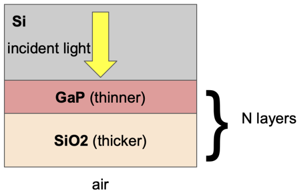

Fig. 4: Diagram of DBR with N layers

From (Eq. 4), (Eq. 5), and (Eq. 6), we can note that every layer of the DBR will cost $213.5[nm]$. Thus, for $N_{bottom} = 7$ layers, the bottom DBR will cost $1.5[\mu m]$.

Next, we design the front DBR with the goal of optimizing total absorption in the intrinsic layer. To measure absorption, we use a power conservation argument to relate reflectance R, transmittance T, and absorbance A as:

$$R + T + A = 1 \tag{12}$$

Modeling the entire photodetector with the TMM matrix and varying the top DBR layers N_{top}, it appears $N_{top} = 3$ is the optimal number of stacked layers to maximize absorbance. Thus, the top DBR contributes a thickness of $0.64[\mu m]$.

C. Optical Cavity

At the operating wavelength, the refractive index [2] of silicon (and thus, the cavity) is:

$$n_{cavity}(\lambda = 850[nm]) = 3.6393 + j \cdot 0.0047757 \tag{13}$$

For optimal absorption, we desire $\lambda = 850[nm]$ to experience resonance. Thus, we need a cavity length defined by:

$$d_{cavity} = \frac{m\lambda}{2Re\{n\}} \tag{14}$$

Where m is the mode of the resonant wave. The equation demonstrates that the cavity length per mode used costs a thickness of $116.8[nm]$.

The cavity consists of the PIN setup. From Fig 2, we know a range of valid intrinsic thicknesses to use. To form low-resistance ohmic contacts and minimize contributions to RC delay, a doping level of $N_a = 1 \cdot 10^{18}[cm^{-3}]$ and P-region thickness $d_P = 75[nm]$ for the p-region appears acceptable [4]. For the N-region, a doping level of $N_d = 1 \cdot 10^{18}[cm^{-3}]$ and N-region thickness of $d_N = 75[nm]$ appears acceptable [4].

Because the P- and N- regions are assigned a fixed thickness, and because of the resonance condition, the cavity must be a fixed length. Thus, $d_{intrinsic}$ is further limited by the relation:

$$d_{intrinsic} = d_{cavity} - (d_P + d_N) = d_{cavity} - 2 \cdot 75[nm] \tag{15}$$

Applying these restraints to the range of intrinsic thicknesses from Fig 2, we find that $2 \leq m \leq 8$ supports both the resonant cavity requirement and the bandwidth requirement.

Noting that, from section B, the front and back DBRs contribute $2.14[\mu m]$ to the stack thickness, it is appropriate to choose $m = 5$. This gives a cavity length of $584[nm]$, and thus, and intrinsic thickness of $434[nm]$. This also gives a total stack thickness of $2.719[\mu m]$, satisfying the stack thickness requirement.

Fig 5 demonstrates a schematic of the final design. Notably, the metal contacts are placed such that they do not interfere with the optical path.

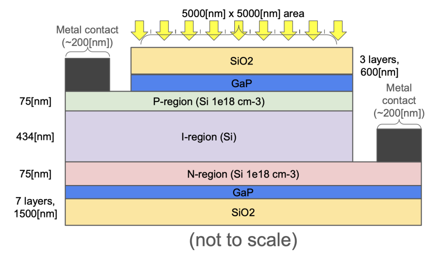

Fig. 5: Schematic of Final RCE Photodetector

D. Quantum Efficiency

Quantum efficiency is given by (Eq. 16):

$$\eta(\lambda) = [1 - R_\lambda] \cdot \zeta \cdot [1 - e^{\alpha(\lambda)d}] \tag{16}$$

Unlike previous sections, the quantum efficiency is not easily calculated analytically. We thus refer to semiconductor simulation platforms. For a given setup, SimWindows offers dark current, photocurrent, and absorption measurements. However, because SimWindows does not account for resonant effects, we cannot model the entire photodetector device.

Instead, we will ONLY simulate the cavity and determine the carrier collection efficiency ζ from (Eq. 16). This parameter is based on the PIN structure, and will thus remain constant in both setups. Using AI, I determined that a reverse-bias of $V = -3[V]$ was acceptable. Relating the photocurrent and quantum efficiency to the responsivity $\Re$ of the system, we find:

$$\Re = \eta \cdot \frac{\lambda}{1.24} = \frac{I_{photocurrent} - I_{dark}}{P_{in}} \tag{17}$$

Thus, it is possible to calculate ζ:

$$\zeta = \frac{\Re \cdot 1.24}{\lambda \cdot [1 - e^{\alpha(\lambda)d}]} \tag{18}$$

Using a power input of $P_{in} = 100[mW/cm^2]$, we obtain $J_{photocurrent} = 2.287 \cdot 10^{-3}[A/cm^2]$, $J_{dark} = 8.05 \cdot 10^{-16}[A/cm^2]$, and an absorption $[1 - e^{-a(\lambda)d}]$ of 3.34%. This gives $\zeta = 99.8\%$. Since the light input was set to start in the intrinsic layer, $[1 - R_\lambda] = 1$

From section B, modelling the entire TMM system gives $A = 93.9\% = [1 - e^{-a(\lambda)d}]$. Since we only care about light that enters the cavity, we once again set $[1 - R_\lambda] = 1$. Thus, a final quantum efficiency of $\eta = 94\%$ is achieved, satisfying the design restraint of $\eta > 50\%$

E. Bit Error Rate (BER)

I now seek to characterize our device performance. The BER of a photodetector can be related to the probability of mistaking a 0-bit for a 1-bit P_0 and the probability of mistaking a 1-bit for a 0-bit P_1 as:

$$BER = \frac{1}{2}(P_0 + P_1) \tag{19}$$

We can model the probability of a measured number of photons m given an expected measurement of $\bar{m}$ with a Poisson distribution:

$$P(m) = \frac{(\bar{m})^m \cdot e^{-\bar{m}}}{m!} \tag{20}$$

When detecting 0- and 1-bit signals, it is necessary to set a photon detection threshold to distinguish both. Earlier, it was found that the dark current was extremely small. Thus, a threshold of 1 appears appropriate. This sets P_0 and P_1 to the following respective equations:

$$P_0(m > 0) = 1 - \frac{\bar{m}_{dark}^0 \cdot e^{-\bar{m}_{dark}}}{0!} \tag{21}$$

$$P_1(m = 0) = \frac{\bar{m_I}^0 \cdot e^{-\bar{m}_I}}{0!} \tag{22}$$

where $\bar{m}_{dark} = \frac{i_{dark} t_b}{q}$ and $\bar{m}_I = \bar{m}_{dark} + \frac{\eta P \lambda}{hc \cdot \text{bps}}$. Calculating the BER at $50[Gbps]$ and optimizing power P such that $BER < 10^{-9}$, we find the power threshold to be $P = 0.289[\mu W] = 1156[mW/cm^2]$

F. Signal-to-Noise Ratio (SNR)

The SNR of a photodetector system can be given as:

$$SNR = \left(\frac{\bar{i}}{\sigma_i}\right)^2 = \frac{\bar{i}^2}{2e \cdot \bar{i} \cdot B} \tag{23}$$

where $\bar{i}$ is the mean input current, σ_i is the total noise current, e is the elementary charge constant, and B is the noise bandwidth. From section E's power calculation, we can calculate the associated current $\bar{i} = \eta \frac{0.85}{1.24} P$ and the noise bandwidth using $B \approx \frac{1}{2 \cdot \tau_{int}} = \frac{bps}{2}$. Thus 20[dB] is achieved.

III. Summary & Conclusions

A. Summary and Conclusions

I have demonstrated the feasability of an RCE-PD design with the aforementioned restraints. Overall, the system performs with a thickness of $2.7[\mu m]$, $\eta = 94\%$, $P(BER < 10^{-9}) = 0.289[\mu m], SNR = 20[dB]$, with a reverse bias of $V = -3[V]$ and detector area of $5[\mu m] \times 5[\mu m]$.

For further optimization, an analysis of the impact of of electrical resistivity on the device performance could be considered. I mitigated this by setting the P and N regions to specific thicknesses and doping levels, but am not certain of the extent to which it mitigates the effects.

B. use of AI

In the beginning stages of the design, I used chatGPT to find relevant design philosophies on resonant cavities and PIN photodiodes. The prompts were mainly for reminding myself of past concepts in the course.

In the middle stages of the design, I used chatGPT to help me decide on $P-$ and $N-$ region doping levels and thicknesses. The slides do not detail good design philosophies for these parameters, and I have not had prior experience with setting these values. I prompted for sources but could not get reliable links to findings despite specific prompting. This is likely an effect of AI hallucation. However, I found a source [4] that was somewhat consistent with AI's recommendations. Its reasoning ultimately seems correct.

I also used it to determine my metal contact widths. I could not find much of any literature on an appropriate width for contacts.

For the end stages, I wanted to compare my photodetector parameters to other designs, but could not get chatGPT to give me reliable links. When I did get links, the photodetector design would often have different fundamental design parameters, such as changing the active region material or using another type of photodetector design (APD, MSM, and waveguide-integration would come up often).

Finally, I gave AI the entire design project prompt and got the following design:

For the DBR mirrors, use Si/SiO_2. Make the bottom 8 pairs (thickness $1.65\mu m$), and the top 3 pairs (thickness $0.62\mu m$). Make the intrinsic layer $300nm$. Place SiO_2 spacers to fulfill the resonant cavity condition. Quantum efficiency $\eta \approx 0.8$. $f_{3dB} = 60[GHz]$. Reverse bias $V = -5[V]$. For desired BER, set $P = 0.48[\mu W]$.

The design outputs closely-resemble mine, with the only difference likely accounted for by the AI's use of Si for the DBR high-index layer as opposed to my use of GaP.

References

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APPENDIX

DESIGN AND SIMULATION PARAMETERS

TABLE I: Design and simulation parameters for the 850 nm silicon resonant-cavity enhanced photodiode.

Category	Parameter	Value
Optical Parameters		
Wavelength	λ	850 nm
Active material		Silicon (Si)
Refractive index (Si)	n_{Si}	$3.6393 + i0.0047757$ [2]
Refractive index (GaP)	n_{GaP}	3.1621 [2]
Refractive index (SiO2)	$n_{\mathrm{SiO_2}}$	1.4525 [2]
Incident polarization		TE
Incident angle	θ_i	0 rad
Cavity Geometry		
Cavity order	m	5
Total cavity length	d_{cavity}	584 nm
Intrinsic layer thickness	d_i	434 nm
P-layer thickness	d_P	75 nm
N-layer thickness	d_N	75 nm
Doping Parameters		
P-layer doping	N_A	1×10^{18} cm^{-3}
N-layer doping	N_D	1×10^{18} cm^{-3}
Intrinsic layer doping		Undoped
Electrical Parameters		
Detector area	A	25 μm^2
Load resistance	R_L	50 Ω
Reverse bias voltage	V_R	$-3V$
Saturation velocity	v_{sat}	1×10^5 m/s
SimWindows Parameters		
Power input	P_{in}	100 mW/cm^2
Photocurrent Density	$J_{\mathrm{photocurrent}}$	$2.287 \cdot 10^{-3}\ A/cm^2$
Dark Current Density	J_{dark}	$8.05 \cdot 10^{-16}\ A/cm^2$
Simulation Radius	r	3.989 μm
I-layer absorbance	$[1 - e^{-a(\lambda)d}]$	3.34%
Left-contact voltage	V_{left}	0 V
Right-contact voltage	V_{right}	3 V
TMM Parameters		
System absorbance	A	93.4%
Top DBR layers	N_{top}	3
Top DBR thickness		0.6 μm
Top DBR reflectance	R_{top}	87.6%
Bottom DBR layers	N_{bottom}	7
Bottom DBR thickness		1.5 μm
Bottom DBR reflectance	R_{bottom}	99.9%
Device Outputs		
Stack thickness		2.7 μm
Quantum efficency	η	94%
3dB bandwidth	f_{3dB}	95 GHz
BER Power Threshold	P_{BER}	0.289 μW
SNR at BER Power	SNR	20 dB

KEY AI PROMPTS AND RESPONSES

1. Question about P and N parameters (couldn't find good sources online)

I am designing a resonant-cavity enhanced photodiode operating at a wavelength of 850 nanometers and an active region of silicon. What are good P and N doping levels and thicknesses?

Summarized Response

$N_A, N_D = 5 \cdot 10^{18} - 1 \cdot 10^{19} cm^{-3}$ *for good ohmic metal contacts and maintaining a negligible level of free-carrier absorption.* $t_A, t_D = 50 - 100nm$ *for parasitic capacitance and parasitic absorption minimization.*

2. Question about metal contacts (couldn't find good sources online)

my design utilizes this setup for metal contacts (design is constant out-of-page) [context: gave AI my diagram in Fig 5. What are good thicknesses? ignore the ones already on the image.

Summarized Response

Using nickel or aluminum, set in range $100 - 300nm$

3. Question about validity of dark current measurement (felt my dark current measurement was off)

give me the expected dark current of a PIN setup with P thickness at 75nm doped at $1e18[cm^-3]$ intrinsic thickness 434nm no doping, N thickness at 75nm doped at 1e18$[cm^-3]$. Using silicon at lambda=850nm.

Summarized Response

Expect 1-10pA

4. Question about reverse-bias voltage (found general values but wanted to see if AI had a specific value in mind.

Summarized Response

"Paper-ready sentence: A reverse bias of approximately 3 V was applied, which is sufficient to fully deplete the 434 nm intrinsic region and establish a strong electric field for efficient carrier sweep-out, while avoiding excessive dark current or tunneling effects."

The AI noted that going above -5V gives no real advantage. We want the reverse bias around -3V so that the system is not working near the depletion edge. If the latter occurred, the i-region would not be very efficient.

5. Entire design prompt (to compare with simulated results)

Summarized Response

For the DBR mirrors, use Si/SiO_2. Make the bottom 8 pairs (thickness $1.65\mu m$), and the top 3 pairs (thickness $0.62\mu m$). Make the intrinsic layer $300nm$. Place SiO_2 spacers to fulfill the resonant cavity condition. Quantum efficiency $\eta \approx 0.8$. $f_{3dB} = 60[GHz]$. Reverse bias $V = -5[V]$. For desired BER, set $P = 0.48[\mu W]$.