Study of Hexagonal Photo-diode for Efficient Side-coupling to Silicon Wave-guide

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Outline

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Motivation

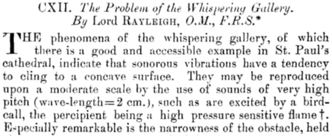
- High-speed, low power data communication on-chip as well as off-chip $\rightarrow$ Optical interconnects.
- Micro-scale on-chip receivers e.g. photo-detectors $\rightarrow$ Lower area footprint, power consumption.
- Scaling down conventional photo-detectors: smaller width for light trapping $\rightarrow$ lower sensitivity!
- Whispering Gallery Mode (WGM) structures $\rightarrow$ Efficient light trapping.
- Micro-scale Silicon waveguide + WGM photo-diode $\rightarrow$ Ideal setup for Si photonics.

(a) St. Paul's Cathedral, London

(b) Gol Ghumez, Bijapur, India

(c) Total Internal Reflection

Figure: Whispering Gallery Structures



CXII. *The Problem of the Whispering Gallery.*
By Lord Rayleigh, *O.M., F.R.S.**

THE phenomena of the whispering gallery, of which there is a good and accessible example in St. Paul's cathedral, indicate that sonorous vibrations have a tendency to cling to a concave surface. They may be reproduced upon a moderate scale by the use of sounds of very high pitch (wave-length=2 cm.), such as are excited by a bird-call, the percipient being a high pressure sensitive flame†. Especially remarkable is the narrowness of the obstacle, held

Figure: Study of Whispering Gallery by Lord Rayleigh

- Working principle of WGM - Total Internal Reflection (TER) at each incidence.
- Fig. 5 shows WG structures for sound waves.
- Can WG principle be used to 'retain' incident photons longer in the photo-diodes?

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Proposed Structure - WGM Photodiode

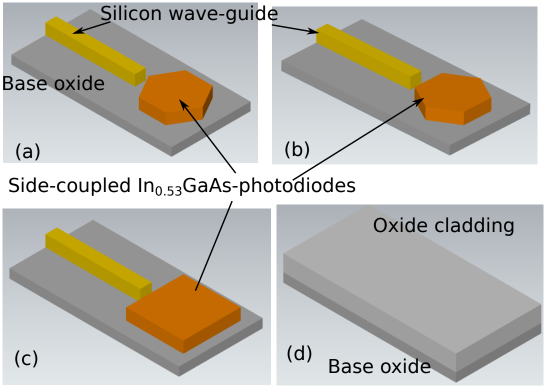

Figure: Hexagonal $In_{0.53}GaAs$ photo-diode at the end of Si waveguide, with two configurations (a) and (b). (c) rectangular photo-diode coupled to the waveguide at the end. (d) Waveguide embedded in oxide cladding.

- Hexagonal structure $\rightarrow$ TER at all the faces $\rightarrow$ Longer retention of light $\rightarrow$ higher sensitivity.
- Hexagonal disc of photodiode (PD) end-coupled to Silicon waveguide is ideal!
- TER efficient at certain angles of incidence $\rightarrow$ optimization of disc rotation-angle w.r.t. the waveguide direction.
- Compared two photo-diode concepts - traditional rectangular stripe, and proposed hexagonal WGM structures
- Structures generated using "Structure Generator and Mesher" by *SemiVi*.

Photodiode Geometry Determination

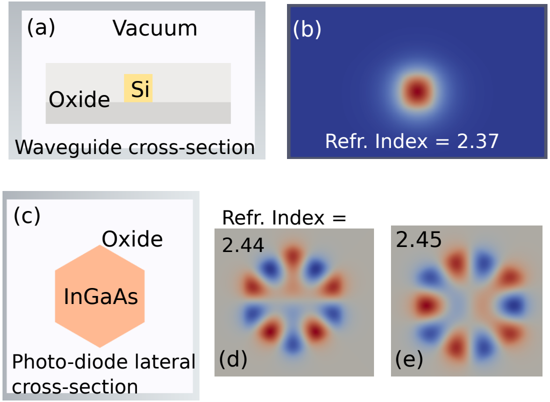

Figure: (a) Cross-section of the waveguide and (b) Modal field in it. (c) Lateral cross-section of the hexagonal InGaAs disc. (d) and (e) Whispering gallery modes supported by it.

- Si waveguide cross-section optimized for compactness and mode-confinement. Dimension: 260nm $\times$ 260nm
- Effective index of Si WG determined by mode calculations of the vertical cross-section.
- Similarly, effective index of WGM modes calculated by mode calculations of the lateral cross-section.
- For optimal coupling, side-length of the regular hexagonal InGaAs disc is optimized, such that effective indices of Si WG and WGM modes are close.
- Mode calculations performed using “Mode Solver” by *SemiVi*.

FDTD Simulation Setup

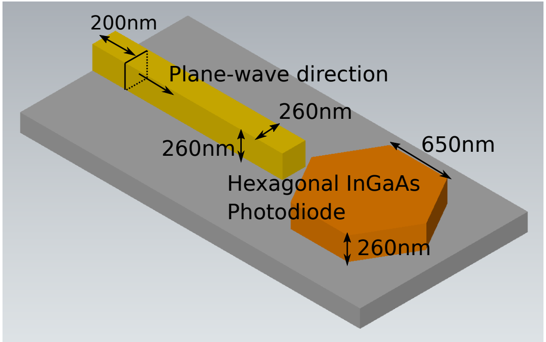

Figure: Hexagonal $In_{0.53}GaAs$ photo-diode at the end of Si waveguide. Various dimensions are shown in the figure.

- Uniform grid-spacing of 20nm along x,y,z axes. Grid size: $92 \times 43 \times 45 = 178,020$ vertices.
- Uniform plane-wave source placed in the plane perpendicular to the waveguide 200nm away from the start.
  - Intensity - 1000W,
  - Wavelength - 1.35μm,
  - Confined to the cross-section of the waveguide.
- CPML BCs active in last 10 layers at all the boundaries of the simulation domain. All the boundary layers located in the 'vacuum' padding.
- Hardware-accelerated "FDTD Solver" by *SemiVi* used for the simulations.
- Nvidia GPU 'RTX 3090' used (10k cuda cores).

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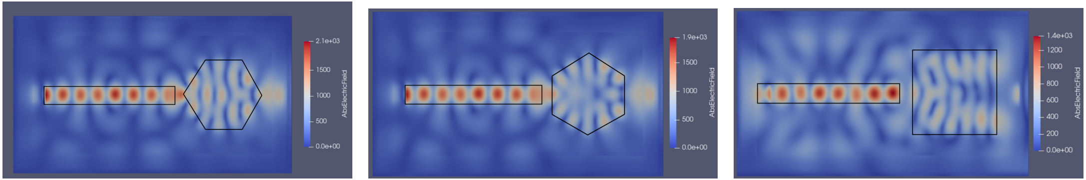
FDTD Simulation Results



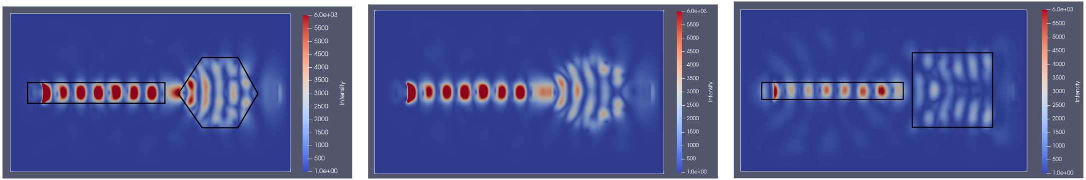
(a) Hexagonal Photodiode (b) Rotated Hexagonal Photodiode (c) Rectangular Photodiode

Figure: Spatial distribution of abs. electric field in the horizontal cross-section at the middle of the waveguide.

- FDTD simulations performed for 200 fsec or 8994 time-steps.
- Magnitude Electric field ($|\vec{E}(\vec{r})|$) is averaged over last 20 fsec.
- Averaged $|\vec{E}(\vec{r})|$ plotted in the horizontal cut-plane in the above figure.

- The field develops a peculiar pattern in the hexagonal structures similar to the WGMs.
- In the hexagonal structures, whispering-gallery mode is indeed actuated by the waveguide.
- In contrast, rectangular PD does not exhibit these modes!

Calculations of coupling strength



(a) Hexagonal Photodiode (b) Rotated Hexagonal Photodiode (c) Rectangular Photodiode

Figure: Spatial distribution of intensity in the horizontal cross-section at the middle of the waveguide.

- In a photo-diode, e-h generation is proportional to the light intensity.
- To estimate e-h generation, intensity is calculated in the photo-diode at time = 190 fsec.
- Intensity in the hexagonal structures is higher than that in the rectangular ones.

Structure	Int. abs. field $V/m{*}\mu m^3$	Int. intensity $W/m^2{*}\mu m^3$
WGM diode	245.5	413.18
Rotated WGM diode	221.77	378.87
Rect. diode	167.49	206.99

Hexagonal structure provides better coupling to the waveguide and better sensitivity.

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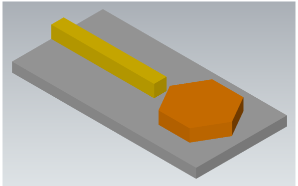
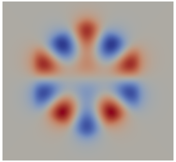
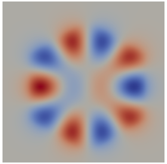
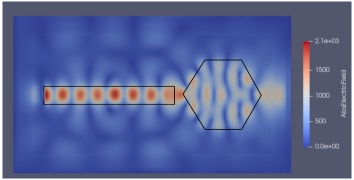
Conclusions









- Studied the effect of hexagonal WGM structure on the coupling strength between Si wave-guide and $In_{0.53}$GaAs photodiode.
- Geometry of the WG and the hexagonal PD set such that the hexagonal structure exhibits WGM close to the refractive index of the waveguide.
- Hexagonal structure provides better coupling to the waveguide and better sensitivity compared to the rectangular structures.