

# Active Silicon Guided-Wave Photonics

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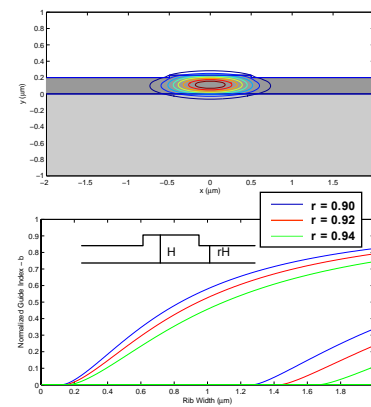
In collaboration with

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**Goal:** *Si/SiO<sub>2</sub> system well proven for passive filters & thermo-optic reconfiguration*

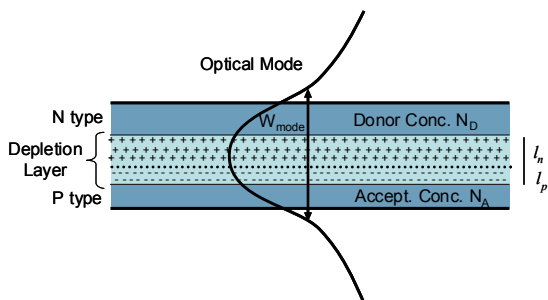
Extend capabilities of Si/SiO<sub>2</sub> system with *active* components

- Emitters & Gain**
  - Er-based emitters – LED's & possibly lasers
  - Explore *electrical pumping* & compatible geometries
  - Optical pumping for gain blocks
- Modulators & Rapidly Tunable Filters**
  - Reverse-biased junction depletion-mode devices
  - Mach-Zehnders
  - Tunable ring resonators, coupled and cascaded rings, channel drops
  - Grating-based and photonic crystal-based  $\mu$ -resonators
- Fabrication & Design for low-loss guides, high-Q resonators**
  - Optimized guide structures compatible with active functionality
  - Practical fabrication sequence compatible with active functionality
  - Low-loss resonator designs, minimize scattering & bend losses
  - Exceptionally high index provides scaling to ultra-compact components, high integration potential



- Thin Planar-Like Ribs on SOI**
- Provides single mode at 1.55 $\mu$ m with reasonable dimensions
  - Small rib height and wet-etch expected to give low surface roughness and low propagation loss
  - Compatible with thin-film structures (Er/SiO<sub>2</sub> deposition or implantation)
  - Waveguide widths in 1–2 $\mu$ m range can be fabricated using standard projection lithography
  - Ribs formed by CMOS compatible wet-etch process

## Simple Scaling Laws for Interferometric Devices:



Active Depletion-Based Plasma Index:

$$\Delta n_{real} = \left( \frac{\partial n_{real}}{\partial N} \Delta N \right) \cdot \Gamma_N + \left( \frac{\partial n_{real}}{\partial P} \Delta P \right) \cdot \Gamma_P$$

For depletion, carrier density change is just doping level

$$\Delta N = N_D \quad \text{and} \quad \Delta P = N_A$$

and confinement factors are given by

$$\Gamma_P \equiv \frac{l_p}{W_{mode}} \quad \text{and} \quad \Gamma_N \equiv \frac{l_N}{W_{mode}}$$

To get depletion distances  $l_p$  and  $l_N$  invoke Gauss's Law:

$$\nabla \cdot D = \rho \Rightarrow \frac{dE}{dx} = \frac{-eN_A}{\epsilon_0} \Rightarrow E_{max} = \frac{-eN_A}{\epsilon_0} \cdot l_p$$

yielding

$$l_p = \frac{|E_{max}| \epsilon_0}{eN_A} \quad \text{and} \quad l_N = \frac{|E_{max}| \epsilon_0}{eN_D}$$

and thus the effective index change

$$\Delta n_{real} = \left( \frac{\partial n_{real}}{\partial N} + \frac{\partial n_{real}}{\partial P} \right) \frac{\epsilon_0 E_{max}}{e W_{mode}}$$

For an interferometric structure, we need

$$\frac{2\pi \Delta n_{real} L}{\lambda} = \pi$$

yielding the **KEY SCALING RESULT** (independent of doping, thicknesses, etc.):

$$\frac{L}{W_{mode}} = \frac{\lambda e}{2\epsilon_0 |E_{max}| \left( \frac{\partial n_{real}}{\partial N} + \frac{\partial n_{real}}{\partial P} \right)}$$

Using actual numbers for the plasma effect and breakdown field in silicon

$$\left( \frac{\partial n_{real}}{\partial N} + \frac{\partial n_{real}}{\partial P} \right) \approx -3.2 \times 10^{-21} \text{ cm}^{-3} \quad \text{and} \quad E_{max} \approx 3 \times 10^5 \text{ V/cm}$$

We get

$$\frac{L}{W_{mode}} = 1.2 \times 10^4$$

so a design for  $W_{mode} = 0.2 \mu\text{m}$  gives  $L = 2.4 \text{ mm}$ .

If we want to minimize  $L$  we might choose the limiting case of just depleting out the full thickness of the layer / when we reach breakdown and  $W_{mode} = t$  (thus maximizing the plasma index change). In this case,

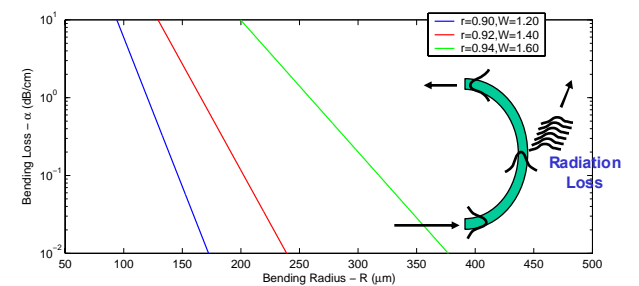
$$l_p + l_N = t = \frac{|E_{max}| \epsilon_0}{e} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \quad \text{or} \quad \left( \frac{N_A N_D}{N_A + N_D} \right) = \frac{|E_{max}| \epsilon_0}{e \cdot t}$$

and integrating Gauss's Law to get voltage yields

$$(V_d + V_a) = \frac{|E_{max}|^2 \epsilon_0}{e} \left( \frac{N_D + N_A}{N_D N_A} \right) \quad \text{or} \quad E_{max} = -2(V_d + V_a)^{1/2} \left( \frac{e}{2\epsilon_0} \right)^{1/2} \left( \frac{N_D N_A}{N_D + N_A} \right)^{1/2}$$

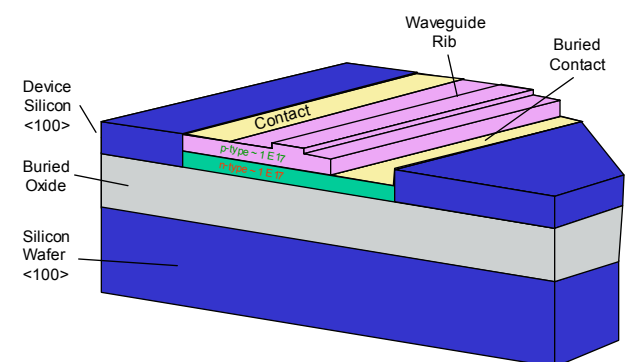
For  $t = 0.2 \mu\text{m}$ , and balanced P and N doping levels, we get

$$N_A = N_D = 2 \times 10^{17} \text{ cm}^{-3} \quad \text{and} \quad (V_d + V_a) \approx 6 \text{ V}$$



- Efficient signal routing in SOI waveguide devices requires small bending losses
- There is a trade-off between rib height and rib width and the bending loss (shallow rib  $\Rightarrow$  less lateral confinement  $\Rightarrow$  more bending loss)
- Design scales by increasing the rib height & decreasing rib width to remain single-mode for reduced bending losses, more compact devices

## Initial Test Vehicle for Junction Depletion SOI Devices

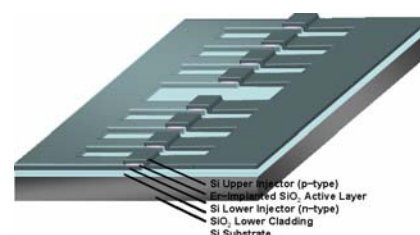


## Example of mask cell with active and passive ring filters coupled to guides

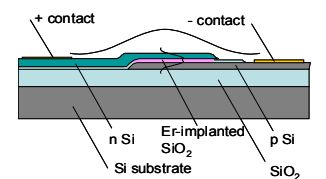


## Future Work and Devices:

- Optimize Design & Fabrication**
  - Gain understanding of losses, optimize fabrication/process technology
  - Scale to smaller dimensions, tighter bends,  $\mu$ -resonators
- Add Erbium Emission & Gain**
  - Overlap ridge waveguide approach
  - Ring and grating resonators
  - Coupled tunable filters
  - Optical & Electrical pumping
  - Laser compatible with active components



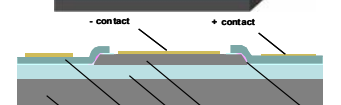
Grating-based Erbium  $\mu$ -resonator



Overlap Ridge Waveguide



Ring Structures



Pump Wavelength Multiplexer



Signal Output Coupler



Er-doped SiO<sub>2</sub> Waveguide Ring Segment