Abstract:
We demonstrate horizontal slot waveguides using high-index regions of polycrystalline and single crystal silicon separated by a 10 nm layer of silicon dioxide. Within the C-band, we measure waveguide propagation loss of 7 dB/cm and ring resonators with an intrinsic quality factor of 82,000. The electric field of the optical mode is strongly enhanced in the low-index oxide layer, which is a favorable condition for modal gain if an appropriate material gain can be incorporated into the slot region. Our choice of high-index materials enables these structures to serve as a platform for electrically pumped silicon-based light sources.

Figure 1: Mode profile for y-polarized slot mode using silicon and oxide.

Summary of Research:
The last major functions yet to be demonstrated on the silicon photonic platform are electrically pumped amplification and lasing within a silicon waveguide. One possible solution is to use the slot waveguide geometry [1,2]. A slot waveguide is formed by placing a subwavelength slot of low refractive index in between two regions of high refractive index [3]. Electromagnetic boundary conditions create an optical mode with a large enhancement of the electric field inside the low-index region, as shown in Figure 1. The strong mode overlap makes slot waveguides an excellent candidate for amplification when combined with a gain material such as erbium-doped silicon-rich oxide or nitride.

Slot waveguides fabricated in silicon offer the possibility of electrically exciting a gain material by carrier tunneling through the slot region [1]. We choose to work with a “horizontal slot” configuration where the different layers can be formed by deposition and growth techniques with nanometer-scale accuracy and sub-nanometer surface roughness. In a horizontal slot waveguide, special consideration must be given to the materials used in the high-refractive-index layers. Crystalline silicon would ideally be used for both the top and bottom layers due to its excellent optical and electrical properties, but layers of crystalline silicon cannot be deposited by standard fabrication techniques. Instead we choose to work with a bottom layer of crystalline silicon-on-insulator (SOI) and a top layer of deposited polycrystalline silicon (polysilicon). Although polysilicon is an inhomogeneous material and hence inherently has some optical loss due to scattering, channel waveguides have recently been demonstrated with losses less than 10 dB/cm [4,5]. Here we demonstrate the first use of polysilicon in a slot waveguide configuration.

The fabrication of our slot waveguides is done on a commercial four-inch SOI wafer. We start with a 250 nm layer of single-crystalline silicon on a 3 µm buried oxide layer, then thin the top silicon layer to 145 nm.
by thermal oxidation and remove the grown oxide with hydrofluoric acid. Then we grow a 10 nm silicon dioxide layer for the slot region using a dry thermal oxidation recipe at 950°C. This leaves a 140 nm bottom layer of crystalline silicon. We deposit a 120 nm top layer of amorphous silicon by low pressure chemical vapor deposition (LPCVD) at 550°C and anneal the wafer in N₂ at a maximum temperature of 1100°C to crystallize the film into polysilicon. We determine the rms roughness of the top surface to be 0.5 nm by AFM.

A cross-sectional scanning electron microscope (SEM) image is shown in Figure 2. To pattern waveguides and resonators, we use e-beam lithography and a 100 nm layer of XR-1541 e-beam resist before etching the structures with chlorine-based inductively coupled plasma reactive ion etching (ICP-RIE). Finally we clad the structures in a 3 µm silicon dioxide layer by plasma enhanced chemical vapor deposition (PECVD) before dicing and polishing the end facets of the chip.

We measure the loss in 500 nm-wide waveguides by employing the cutback method. Twenty waveguides are patterned with increasing path lengths but the same number of bends. At a given wavelength, we record the transmission through each waveguide and plot the relative transmission on a logarithmic plot as shown in the inset of Figure 3. The slope of a linear fit gives the waveguide loss, which we measure to be 7.3 dB/cm at λ = 1550 nm with a standard error of 0.4 dB/cm. We repeat the measurement for many wavelengths. The results in Figure 3 show waveguide losses of around 6-8 dB/cm within the C-band gain window of erbium.

We also fabricate and test ring resonator cavities in the horizontal slot configuration. A close scan of a resonance for a 100 µm radius ring at λ₀ = 1552.12 nm is shown in Figure 4. We measure a linewidth Δλ_{FWHM} = 29 pm which corresponds to an undercoupled quality factor Q_{loaded} = 54,000. This corresponds to a propagation loss within the ring α_{ring} = -2 ln(a)/L = 1.693 cm⁻¹ = 7.4 dB/cm and an intrinsic quality factor Q₀ = (2πn_p)/λ₀ α_{ring} = 82,000. To our knowledge this is a higher quality factor than any resonator demonstrated in a vertical slot orientation, which validates our use of the horizontal slot orientation for lower losses.

In conclusion, we have demonstrated slot waveguides and resonators using electrically active high-index materials and a 10 nm thin oxide slot suitable for carrier tunneling. These structures may enable on-chip silicon-based amplifiers and light sources when combined with a suitable gain material in the slot (such as an erbium-doped silicon-rich oxide or nitride) and a forward-biased PIN diode for carrier injection.

References: