Feasibility of Multimode Polycrystalline Waveguides/Devices: Record Low Propagation Loss and Uniform 1x12 MMI Fanout

David Kwong[1], John Covey[1], Amir Hosseini[2], Yang Zhang[1], and Ray T. Chen[1]
[1]Microelectronic Research Center, Department of Computer and Electrical Engineering, University of Texas at Austin, 10100 Burnet Rd. Austin, TX 78758, USA
[2]Omega Optics Inc, 10306 Sausalito Dr, Austin, TX 78789, USA

Author e-mail address: david.kwong@utexas.edu, raychen@uts.cc.utexas.edu

Abstract: We investigate the loss dependence of multimode polysilicon waveguide widths, achieving a record low propagation loss of 3 dB/cm as well as demonstrating a low loss and high uniformity 1x12 multimode interference (MMI) beam splitter.
OCIS codes: (130.3120) Integrated Optics devices; (230.1360) Beam splitters;

On-chip silicon photonic networks are a promising solution for the interconnect bottleneck in high performance microelectronics. While crystalline silicon-on-insulator (SOI) is a heavily utilized platform, photonic devices with large footprints are restricted to the electronic layer. A multi-layer silicon platform would further enable photonic device versatility, as footprint and separation issues are mitigated. In order to maximize such a platform's design flexibility, CMOS compatible silicon deposition methods are strongly desired. Deposition of polycrystalline silicon (polysilicon) is a mature, dopable process that can also realize electrically active photonic devices due to its relatively high (~100cm^2/V-s) [1] electronic carrier mobility. Propagation loss has remained a significant challenge for polysilicon waveguides, which is dominated by two main mechanisms: scattering and absorption at the polycrystalline grain boundaries (bulk loss) and scattering at the core/cladding interfaces (interface loss). Low loss (~6.45dB/cm) polysilicon waveguides, [2, 3] ring resonators [4], and electro-optic modulators [5] formed by Solid Phase Crystallization (SPC) of Low Pressure Chemical Vapor Deposition (LPCVD) amorphous silicon have been demonstrated. Compared to direct deposition of LPCVD polysilicon, SPC of LPCVD amorphous silicon gives superior film qualities, such as smoother surfaces to reduce interfacial scattering and larger grains that result in fewer absorbing boundaries, further lowering the propagation loss [6].

To date, photonic polysilicon research has focused on waveguides and devices in the single mode region with thicknesses of 200-250nm and widths of 300-500nm, where narrower waveguides result in lower loss due to less confinement of light in the polysilicon core, indicating that attenuation is dominated by bulk loss [2]. However, less work exists for wider, multimode polysilicon devices, and it is unknown if the attenuation from bulk loss becomes excessive. For key components such as MMIs for beam splitting, and arrayed waveguide gratings (AWG) for wavelength division multiplexing (WDM), device dimensions can span tens to hundreds of microns [7, 8]. Characterizing the loss of polysilicon at such widths is necessary to determine if these devices can be formed without prohibitively high losses.

We investigate the loss dependence of polysilicon waveguides on the waveguide width, including the multimode region and also present the first large polysilicon photonic device via a low loss, high uniformity 1x12 MMI.

To investigate the loss dependence of polysilicon waveguide widths, we measure the loss of different waveguide widths from 300nm to 10µm. Light is coupled into a 2.5µm wide waveguide which is then tapered to the desired waveguide width using a 2mm long quadratic adiabatic taper. After 5mm of propagation for each waveguide width, the waveguide tapers to 2.5µm for output coupling. By having identical coupling conditions and adiabatic tapers, we analyze the effect of only the waveguide width in this structure.

1x12 MMIs were also fabricated with lengths and widths L_{MMI}=553.4µm and W_{MMI}=60µm, respectively, and access waveguide width W_W=2.6µm, as described in [7]. A fanout design is used to increase the output channel separation to 30µm to clearly resolve the near field image. The output waveguides are tapered adiabatically from 2.6µm to 500nm for single mode output.

A 230nm thick amorphous silicon (a-Si) film is deposited on 2µm of thermally grown SiO_2 using LPCVD with SiH_4 at 550°C. Afterwards, the a-Si is crystallized into polysilicon using a two-step annealing process: 600°C for 30 hours followed by 1000°C for 4 hours. Electron beam lithography and Reaction Ion Etching (RIE) are used to pattern the waveguides and the MMIs. Plasma-enhanced Chemical Vapor Deposition (PECVD) is used to deposit

1µm of SiO_2 for top cladding. A microscope image of the final MMI device is shown in Figure 1(b), and an SEM cross section of a single output waveguide is shown in Figure 1(c). Input and output facets are prepared by cleaving.

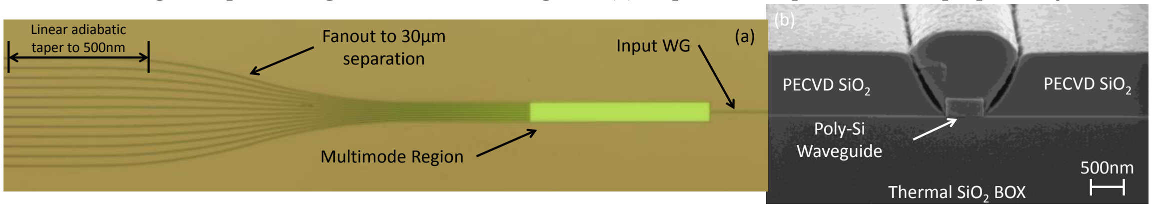

Figure 1-(a) Microscope image of 1x12 polysilicon MMI and (b) SEM cross sectional image of a single polysilicon MMI output channel.

An automated alignment system is used to couple Transverse-Electric (TE) polarized light at 1550nm into the waveguides using a Polarization Maintaining (PM) lensed fiber with a 2.5µm mode field diameter. Figure 2(a) shows the dependence of the propagation loss on the waveguide width, along with the confinement factor which is calculated using a finite element method based mode solver. It can be seen that there are two regions of operation: a bulk loss dominated region when the waveguide is single mode and an interface loss dominated region when the waveguide is multi-mode. In the single mode region, narrower widths yields less loss due to reduced light confinement in the core, which agrees with previous work. However, in the multimode region, the wider waveguides exhibit less propagation loss despite higher core confinement and thus exhibits more dependency on field-sidewall interaction. Such a result vindicates the use of polysilicon in wide, multi-moded photonic devices.

A top down IR camera was used to image the MMI outputs for near field imaging, as shown in Figure 2(b). The 12 bright and uniform output spots indicate a high performance MMI. Loss and uniformity results via high-resolution fiber scanning are forthcoming.

In summary, by varying waveguide width, we demonstrate the lowest polysilicon waveguide propagation loss to date of 3 dB/cm and the first low-loss and high uniformity polysilicon MMI.

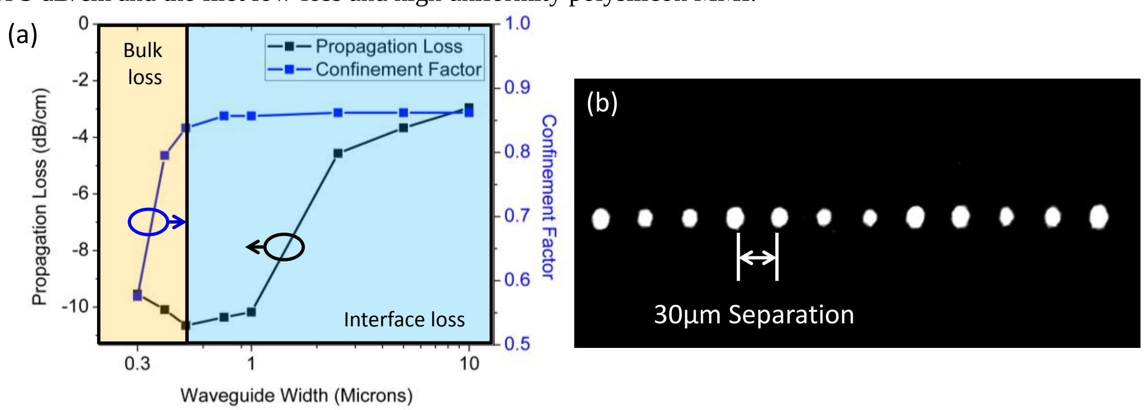

Figure 2-(a) Polysilicon loss and confinement factor as a function of waveguide width. (b) Top down IR image of 1x12 polysilicon MMI output.

This research is supported by the multi-disciplinary university research initiative (MURI) program through the AFSOR, contract # FA 9550-08-1-0394.

References

[1] T. Kamins, *Polycrystalline Silicon for Integrated Circuits and Displays*, 2nd ed. (Kluwer, 1998).
[2] Shiyang Zhu, Q. Fang, M. B. Yu, G. Q. Lo, and D. L. Kwong, "Propagation losses in undoped and n-doped polycrystalline silicon wire waveguides," Opt. Express 17, 20891-20899 (2009).
[3] Q. Fang, J. F. Song, S. H. Tao, M. B. Yu, G. Q. Lo, and D. L. Kwong, "Low loss (~6.45dB/cm) sub-micron polycrystalline silicon waveguide integrated with efficient SiON waveguide coupler," Opt. Express 16, 6425-6432 (2008).
[4] Kyle Preston, Bradley Schmidt, and Michal Lipson, "Polysilicon photonic resonators for large-scale 3D integration of optical networks," Opt. Express 15, 17283-17290 (2007).
[5] Kyle Preston, Sasikanth Manipatruni, Alexander Gondarenko, Carl B. Poitras, and Michal Lipson, "Deposited silicon high-speed integrated electro-optic modulator," Opt. Express 17, 5118-5124 (2009).
[6] L. Liao, D. R. Lim, A. M. Agarwal, X. Duan, K. K. Lee, and L. C. Kimerling, "Optical transmission losses in polycrystalline silicon strip waveguides: effects of waveguide dimensions, thermal treatment, hydrogen passivation, and wavelength," J. Electron. Mater. **29**(12), 1380–1386 (2000).
[7] A. Hosseini et al, "1xN multimode interference beam splitter design techniques for on-chip optical interconnections," IEEE Journal of Selected Topics in Quantum Electronics 17, 510-515 (2011).
[8] P. Dumon, W. Bogaerts, D. Van Thourhout, D. Taillaert, R. Baets, J. Wouters, S. Beckx, and P. Jaenen, "Compact wavelength router based on a Silicon-on-insulator arrayed waveguide grating pigtailed to a fiber array," Opt. Express 14, 664-669 (2006).