

Fundamentals of Silicon Photonic Devices

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This paper offers a brief introduction to silicon photonics including the basic optical waveguide, passive optical circuit performance, the addition of doped p- and n- junctions adjacent to the intrinsic silicon waveguide to inject a current across the waveguide, free-carrier dispersion, performance of the variable optical attenuator (VOA), and a monolithic, dual-function splitter-VOA array circuit.

Key words: silicon, photonic, electronic, optical, attenuator, PLC, VOA

1. INTRODUCTION

The use of silicon has long been established for infrared optics, such as simple lenses and windows and long-wave detection. Today (in 2006) silicon is the material of choice for visible detection, particularly as the imaging element in digital cameras. In some commercial cameras, the wavelength response of silicon has even been extended to the near infrared (to 1,100nm). In addition, the vast expert base in silicon materials, device physics, and processing equipment that has been developed for electronic microcircuits, lay in waiting to address the rapid growth of the fiber optic infrastructure for the transport of information, video, and voice.

There is no doubt about the economic and technical advantages of silicon and it was inevitable that silicon would be employed wherever optic fiber is deployed. Predictably, with the rise in Internet and data transmission, the need for higher speed, broader bands, and lower cost matches all four of the material benefits provided by silicon:

- o Photonic: wide band infrared transparency,
- o Electronic: low noise, high speed integrated circuits,
- o Thermal: high heat conductance, and
- o Structural: rugged 3-dimensional platforms and packages.

These material properties make possible a wide range of integrated electronic and photonic circuits. Reviews of the silicon potential are found in a recent article by Lipson¹ and Jalali². This paper will focus on current and near-term products including the first silicon electro-photonic commercial device - the electrically variable optical attenuator or VOA - and explain the basic construction, operating principals, and device physics. Finally, a new experimental silicon photonic circuit will be described. We begin with an introduction to the silicon optical waveguide and add in electronic functionality.

2. SILICON-PHOTONIC CIRCUIT

Light is confined to the silicon material by a top and bottom cladding of silicon dioxide. The high index contrast between silicon at 3.47 and silicon dioxide at 1.6, does not allow light, at 1550 nm, to extend into the oxide beyond a tenth or so of a micron. A rib structure on the top surface of a silicon chip guides the optical power in the plane of the silicon. An illustration is shown in Figure 1. In this example the depth of the rib edge is 60% of the rib height H. The optical beam is tightly confined above and below by the oxide, but loosely confined laterally, below the ridge

Some properties of the silicon waveguide are quite different from the more familiar silica (SiO₂) waveguide. In Silicon, the minimum turning radius is 250 μm compared to 5,000 μm in silica; the Si index is 3.4 compared to 1.6; and the temperature coefficient, dn/dT , is $18\text{E-}5/\text{C}$ compared to $1\text{E-}5/\text{C}$ silica. Other differences will be described later.

The 1-by-2 splitter, a common passive circuit is used extensively throughout the industry. A new silicon-photonic design has excellent uniformity over an exceptionally broad band, from 1260 nm to 1,650 nm. With the small turning radius, the die size of a 1-by-8 is only 1 mm by 13 mm allowing about 800 die per 150 mm wafer. Another example of a standard commercial circuit is the AWG. Because of material purity and precise geometric control, the silicon AWG has very low crosstalk and excellent ITU grid registration. An example spectrum is shown in Figure 2.

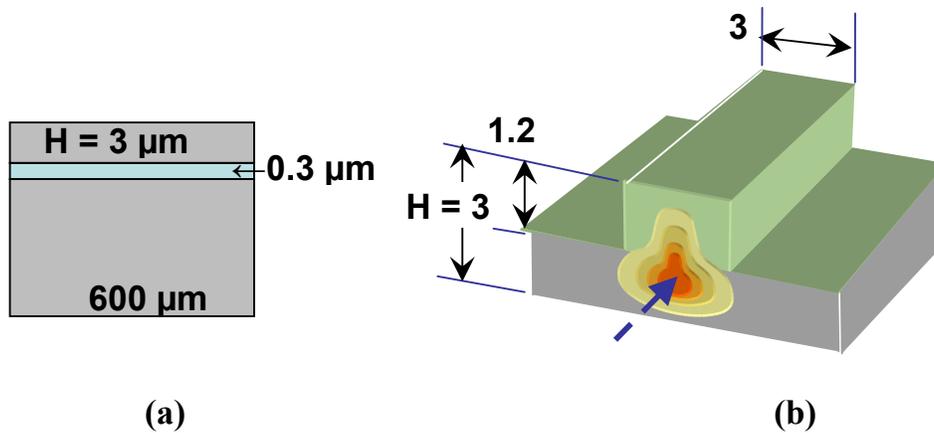


Figure 1. (a) SOI wafer profile showing the $3 \mu\text{m}$ thick top Si where optical waveguides are formed, the $0.3 \mu\text{m}$ BOX that serves as the lower cladding, and the $600 \mu\text{m}$ thick Si substrate. (b) details of a $3 \mu\text{m}$ wide rib waveguide structure with the pear-shaped optical mode power profile shown in cross section.

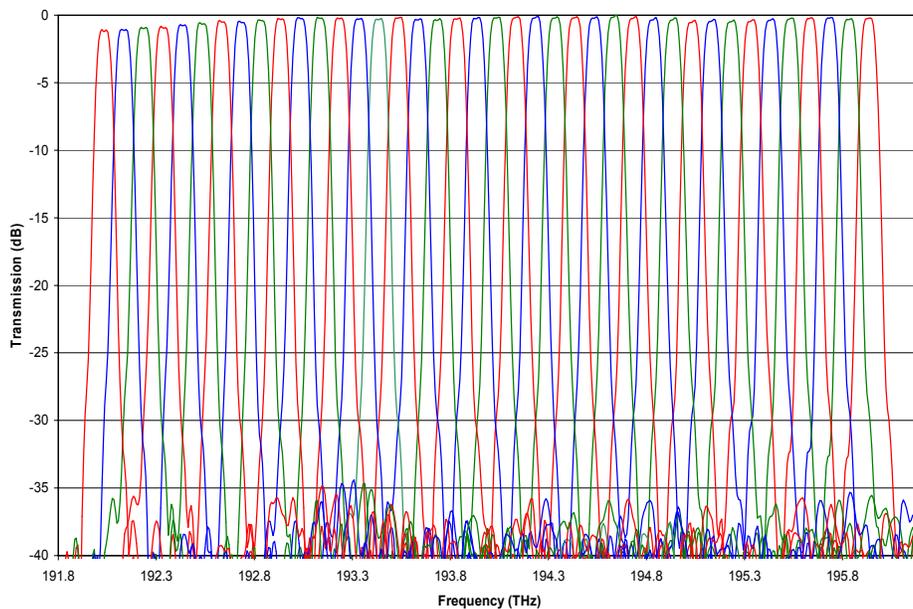


Figure 2. Normalized transmission spectrum of a silicon flat-band AWG showing excellent crosstalk and channel uniformity.

The absolute insertion loss from glass fiber to a Si AWG is a little higher compared to a silica AWG. However, when multiple functions are integrated monolithically, when fiber interconnects are not utilized, the Si AWG has an insertion loss advantage. An example will be presented later in this introduction.

A 3D mode transformer will minimize the coupling loss between a glass fiber and a Si waveguide. This device is shown pictorially in Figure 3. Processes for this structure are similar to MEMS processing which have long been optimized in silicon wafer fabrication facilities. The 3D taper is less than 2 mm long and terminates in a point about $1 \mu\text{m}$ wide.

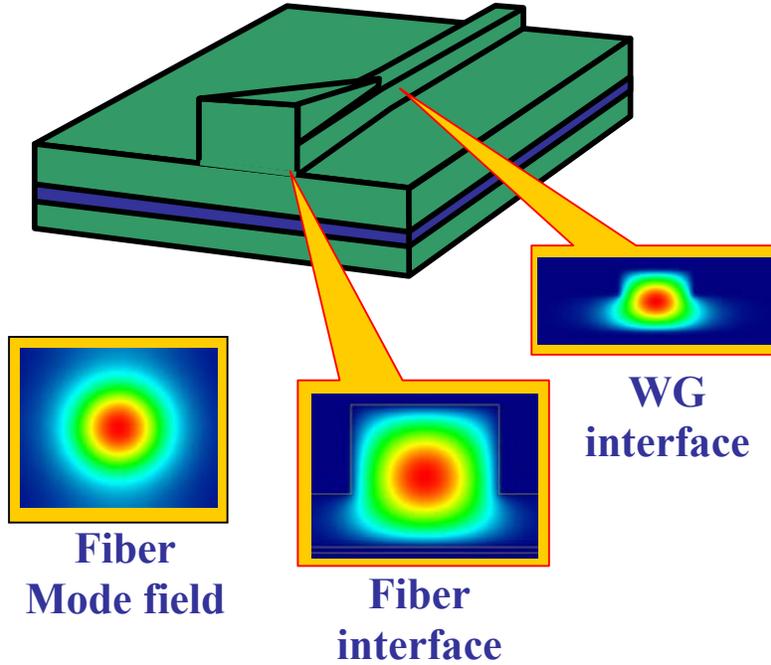


Figure 3. Pictorial of the 3D mode transformer developed for silicon photonics. The insertion loss is reduced from 3.4 dB, without the mode transformer to 0.3 dB. The primary cause of loss is the large area mode tail in the fiber that cannot match the tight mode pattern of the silicon.

3. SILICON ELECTRONIC DEVICE

A great advantage of silicon photonics is its electronic properties, adding the potential of optoelectronic and electrooptic interactions of photons and electrons. This makes possible electrical excitation and manipulation of light as well as optical conversion to electrical signals and even light control of light. Figure 4 illustrates the cross section of a Si photonic waveguide with adjacent p- and n-doped regions. The waveguide region itself is almost intrinsic, but lightly p-type. Electrical contacts to p- and n- regions form the terminals of a *p-i-n* diode, where the i-part (intrinsic) is the waveguide region.

A forward biased current, from the p-region to the n-region, passes through the waveguide. As the current I , flows, the carrier density (cm^{-3}) builds up with a time constant τ to a value

$$N = K_v \cdot I \cdot \tau \quad (1)$$

where K_v is constant approximately equal to the reciprocal of the electron charge and device volume, I is the steady-state current, and τ is the effective carrier lifetime. This charge density resides in the conduction band (for electrons) and valence band (for holes) and hence comprises “free-carriers” capable of flowing freely under the influence of an electric field. In particular, the charges respond to the oscillatory electric field of a light wave.

The classical dispersion theory of a free-carrier gas was developed by Drude and is described in many textbooks. The Drude model, however, does not match too well to the dispersion of free carriers in crystalline silicon and empirical values are most often cited. The linear absorption coefficient, for α and real index of refraction, n , has been determined empirically, first by Schroder³ and later by Soref⁴, by measuring the optical loss of transmitted light through silicon samples of various electron density (N_e) and hole density (N_h), formed by various impurity doping, and sample thickness. The accepted empirical relationships for silicon at room temperature and 1550 nm wavelength are given in Eqs. 2 and 3, where N_e and N_h are the electron and hole density respectively.

$$\alpha = 8.5 \times 10^{-18} \cdot N_e + 6.0 \times 10^{-18} \cdot N_p \quad (2)$$

$$n = -8.8 \times 10^{-22} \cdot N_e - 8.5 \cdot 10^{-16} \cdot N_p^{0.8} \quad (3)$$

At low currents, the index can be precisely controlled finding application in switching and modulation. At high currents, linear absorption dominates and attenuation and modulation can be realized. With the addition of electronics, several optical functions can be realized: attenuator, modulator, phase shifter, switch, gain equalization, detector, amplifier, light emitter. In addition, simple, but useful electronic devices can be monolithically added to the silicon substrate: resistor, capacitor, transistor, temperature sensor, and others. .

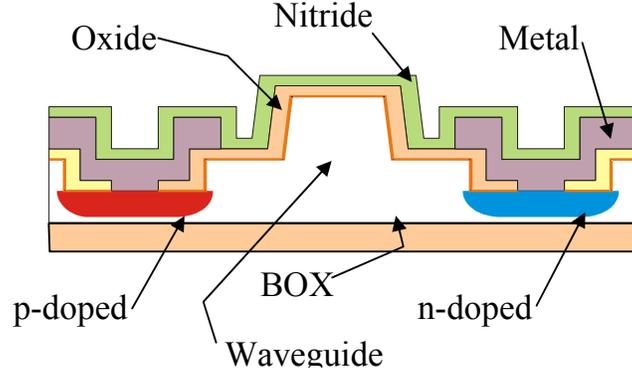


Figure 4. Cross section of a Si photonic waveguide with adjacent p- and n- doped regions. The waveguide region is slightly jp-type, but essentially intrinsic. The Electrical contacts to p- and n- regions form the terminals of a PIN diode.

4. VARIABLE OPTICAL ATTENUATOR

Attenuation in the VOA is realized by the free-carrier absorption mechanism. Free-carriers in this case, comprise a “gas” of electrons and holes in the conduction and valence bands of the matrix of silicon ions. Electrons and holes in their respective bands are free to move about within the bounds of the silicon crystal. Initially, when no light is present, all the charge carriers have a kinetic energy, ($\frac{1}{2} m \cdot v^2$), near the minimum energy points of the bands consistent with the thermal energy of the crystal. The carrier gas is in thermal equilibrium with the crystal lattice.

When a light wave, E-field accelerates an electron or hole to a higher kinetic energy level, the gas heats up, but the heat is quickly transferred to the crystal lattice. The light beam has lost energy equal to the heat energy transferred to the lattice. The amount of light lost, depends on the total number of carriers encountered by the optical wave and the initial optical power in the wave. Let P_n be the optical power entering the electron hole gas and P_o the optical power exiting the gas after traveling a distance L through the free-carrier gas. The relationship shown in Eq. (4), defines the familiar linear absorption coefficient, α .

$$P_o = P_n \cdot e^{-\alpha \cdot L} \quad (4)$$

In general, the linear absorption coefficient is dependent on temperature and wavelength and generalizing Eq. (1) to the form shown in Eq. (5).

$$\alpha = K_e(T, \lambda) \cdot N_e + K_p(T, \lambda) \cdot N_p \quad (5)$$

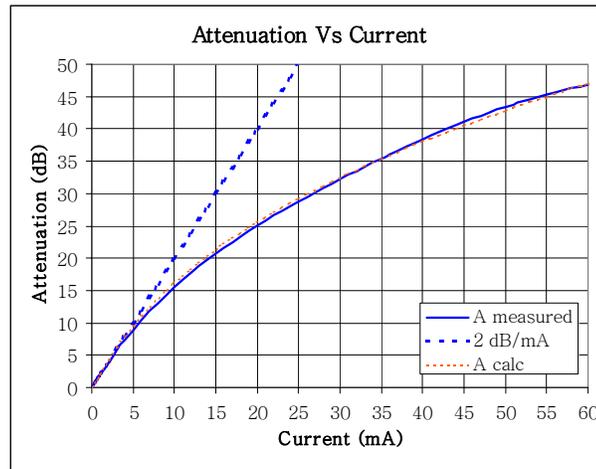
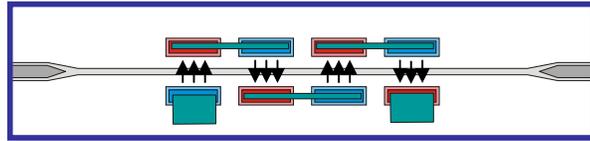
Attenuation is defined as:

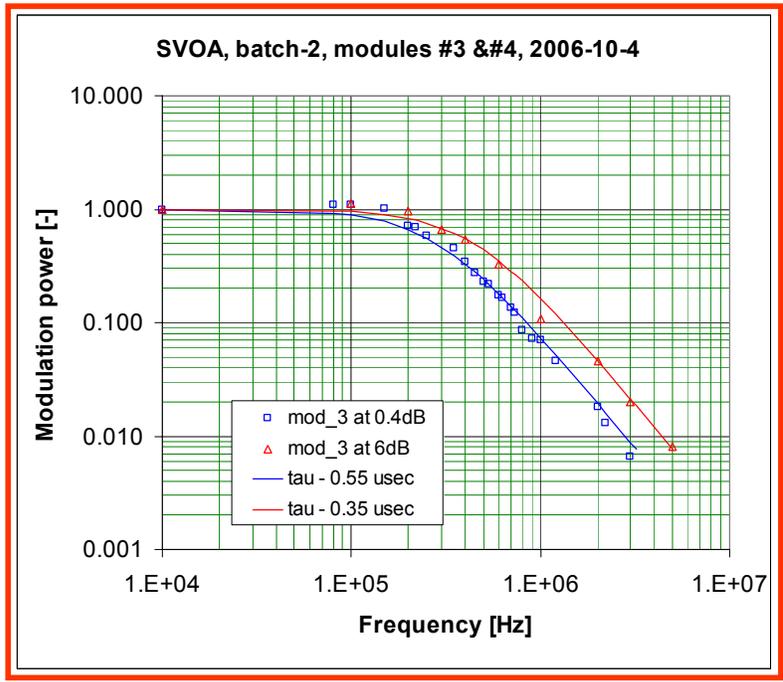
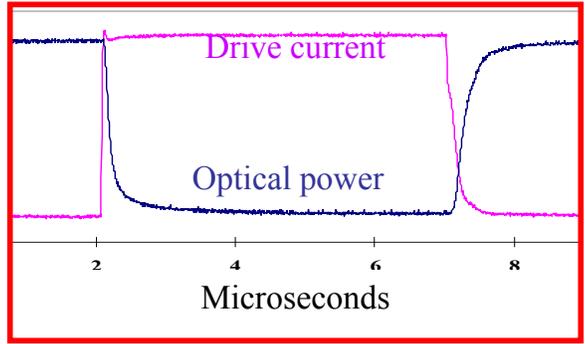
$$A \equiv 10 \cdot \log(P_n / P_o)$$

When converted with Eqs (1, 4 and 5), attenuation becomes:

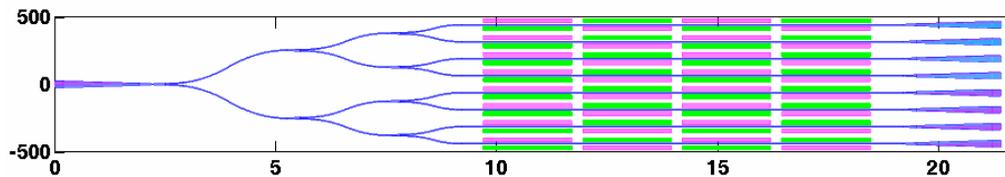
$$A \equiv 10 \cdot \log(e) \cdot L \cdot (K_e + K_h) \cdot K_v \cdot I \cdot \tau \quad (6)$$

Where N_e and N_h are assumed equal to N (defined by Eq. 1).





5. SILICON ELECTRO-PHOTONIC CIRCUIT



6. CONCLUSION

Silicon material and processing methods, thanks to the huge microelectronics' industry, has a level of purity and maturity far exceeding any other. Extending this materials capability to photonics and also merging the two primary device types, photonics and electronics, into one integrated dual functional device brings the benefits of a large economy of scale and wide application far beyond the simple combination of separate devices.

We have shown here a brief introduction to silicon electro-photonics, indeed the electro-photonic device, although proven in production and field environments, has only begun to demonstrate its potential. With research growing in numerous industrial laboratories, one expects to soon be commercially available, 100 Gbps devices for optical communication and novel devices for sensors and transduction.

The device physics of silicon photonics and electronics and the interaction between the two is an open field for discovery and invention. Bring new challenges to the device engineer in design, processing, and packaging.

Recombination injected silicon R. A. Sinton and R. M. Swanson, *IEEE Trans. Electron Devices*, **ED-34**, 1380-1389, (1987).

EXTRA

The steady-state and dynamic performance of the electronic-controlled VOA depends on the free-carrier absorption of electrons and holes within the intersection of a silicon electronic diode and a silicon photonic waveguide. The electro-photonic device is conceptually simple. Attenuation depends only on the free charge within the optical path. However, a proper design for a specific application requires simultaneous optimization of numerous parameters including: voltage, carrier lifetime and mobility, linearity, small-signal bandwidth and large-step response, optical mode profile, polarization, back reflection, stray light, mode mixing, and insertion loss. Silicon also supports 3D physical, MEM-type structures and the dual-taper mode converter is shown as an example.

¹ M. L. Lipson, *J. Lightw. Technol.*, **23**, 4222-4238, (2005).

² B. Jalali, M. Paniccia, and G. Reed, *IEEE Microwave Magazine*, 58-68, June, (2006).

³ D. K. Schroder, R. N. Thomas, and J. C. Swartz, *IEEE Trans. Electron Devices*, **ED-25**, 254-261, (1978).

⁴ R. A. Soref and B. R. Bennett, *IEEE J. Quantum. Electron*, **QE-23**, 123-129, (1987).