Ultrafast, All-Silicon Light Modulator

The ability to send high-speed messages between integrated circuit devices requires both high-frequency receivers and transmitters. The vast majority of integrated circuits are made from silicon-based semiconductors. Suitable receivers of silicon integrated circuits can be constructed from either metal-semiconductor-metal photodiodes[1] or *P*-type, intrinsic, *N*-type (PIN) photodiodes. These receivers are capable of acting as interconnection devices for frequencies up to tens of gigahertz. The transmitter half of this interconnection for silicon has proved to be more problematic. A semiconductor laser has yet to be made from silicon and may prove to be an impossible task. It may be possible to use an optical modulator in place of a semiconductor laser as the transmitter for silicon-based integrated circuits. The refractive index of silicon can be modified by the free-carrier density (the carrier-refraction effect);[2] therefore, the refractive index can be changed by either the injection or depletion of free-carriers.

This effect has been utilized in all-silicon, light-intensity modulators.[3–6] These devices have typically two components: one is an optical phase modulator; the other converts the phase modulation to intensity modulation. In the phase-modulation device, carrier injection into a lightly doped layer provides an extended interaction region wherein the index of refraction may be externally controlled. However, using carrier injection poses two undesirable concerns: the injected current density must be high, and the devices are inherently slow because their speed is limited by the carrier lifetime (nanoseconds to microseconds).

For practical applications, a high-speed, low-power-dissipation, high-modulation-depth, small-sized modulator is desirable. In this article we propose an ultrafast light modulator made on silicon-on-insulator (SOI) substrates. It is a field-effect device, accompanied naturally with low-power dissipation. This modulator is based on carrier depletion instead of carrier injection; hence, its speed may be limited only by the device capacitance and is estimated to be as high as 70 GHz. Most importantly, this modulator is not based on phase modulation. It is a Bragg reflector induced by electric field, which efficiently converts the small index modulation to light-intensity modulation.

Figure 60.9 shows the schematic view of the modulator. The SOI structure acts as an optical waveguide. On top of the silicon layer are interdigitated metal fingers, which form Schottky contacts with silicon. A microstrip line guides the electrical signal to the metal fingers. When the metal fingers are alternately biased, they form forward- and reverse-biased Schottky junctions with silicon. There are larger depleted regions on the reverse-biased sides, as shown in the shaded part of Fig. 60.10. In a *P*-type silicon layer with a hole concentration of $3 \times 10^{18}/\text{cm}^3$, there is a refractive-index difference of $\Delta n = 0.005$ between the depleted and undepleted regions, assuming an optical wavelength of 1.55 μm.[2] The alternately depleted and undepleted areas form a Bragg reflector in the optical waveguide. Applying a time-dependent voltage to the metal fingers modulates the shape of the depleted regions and, in turn, the reflectivity of the Bragg reflector and the light intensity.

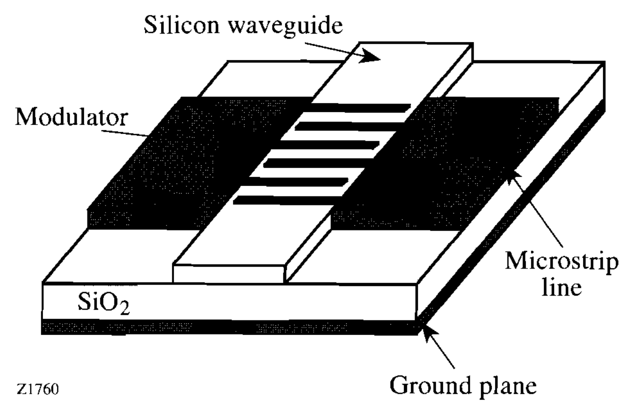

Figure 60.9
A schematic view of the waveguide modulator. The SOI structure acts as an optical waveguide. On top of the silicon layer are interdigitated metal fingers, which form Schottky contacts with silicon. A microstrip line guides the electrical signal to metal fingers.

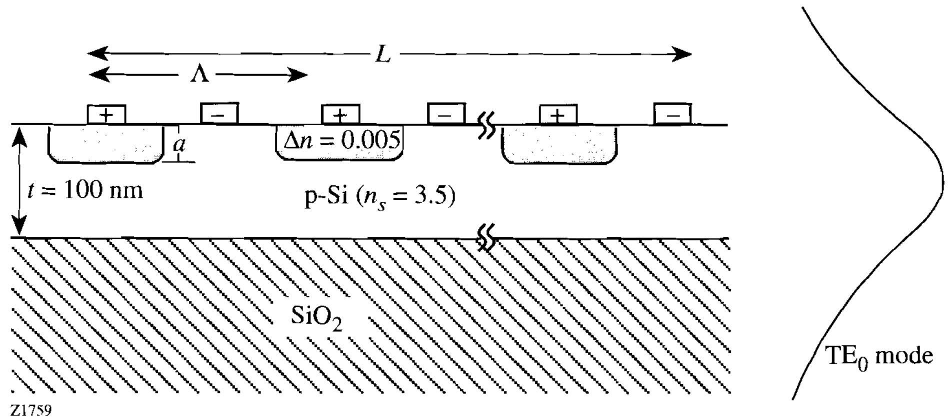

Figure 60.10
The reversed-biased Schottky contacts have larger depleted regions (shaded part), which have a larger refractive index. The alternating depleted and undepleted regions form a Bragg reflector in the waveguide. The electric-field-induced Bragg reflector converts the index modulation to light-intensity modulation. The TE_0 mode profile is shown to the right of the modulator.

The reflectivity, or the modulation depth of this device, can be calculated by using coupled-mode theory.[7] The modulation depth is maximized when the Bragg condition is satisfied, i.e., $\Lambda = \lambda/2$, where Λ is the period of finger electrodes as shown in Fig. 60.10 and λ is the light wavelength in the guiding layer. In this case, the reflectivity can be expressed as $R = \tanh^2(\kappa L)$, where L is the interaction length of the modulator and κ is the coupling constant. If the depleted region is assumed to have a rectangular shape and equal length with the undepleted region (as shown in Fig. 60.10), then κ is given by[7]

$$\kappa = \frac{\omega\varepsilon_0\left[\left(n_s + \Delta n\right)^2 - n_s^2\right]}{4\pi} \times \int_{-a}^{0} \left|E(x)\right|^2 dx, \qquad (1)$$

where ω is the frequency of the optical wave, $E(x)$ is the normalized wave solution of the optical waveguide, a is the depletion width, and n_s is the refractive index of the silicon layer. Here, n_s is taken to be 3.50. The indices of air and silicon dioxide are chosen to be 1 and 1.45. The thickness of the guiding layer is chosen to be 100 nm for single-mode operation and to sufficiently guide the TE_0 mode of light with wavelength of 1.55 μm. (For TM mode, the coupling constant is much smaller, characteristic of Bragg reflectors.) The guided wavelength in this SOI waveguide is 0.72 μm; thus, to satisfy the Bragg condition the period of the finger electrodes is 360 nm.

Since a is a function of the electrode voltage, the modulation depth is also voltage dependent. The modulation depth as a function of biasing voltage is shown in Fig. 60.11 for several interaction lengths. In this calculation, the hole concentration of the silicon layer is set to be $3 \times 10^{18}/\text{cm}^3$, and the built-in voltage of the Schottky contact is 0.5 V, which is typical for metal-semiconductor contacts. It shows that, with 5-V bias, a modulator with interaction length of 300 and 500 μm has a modulation depth of about 40% and 70%, adequate for most applications.

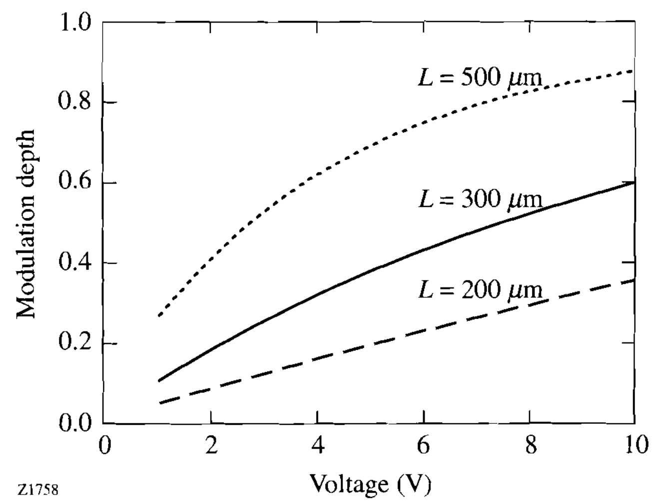

Figure 60.11
The modulation depth of modulators for TE_0 mode with different interaction lengths is shown as a function of biasing voltage. The thickness of the guiding layer is 100 nm, and the doping is $P = 3 \times 10^{18}/\text{cm}^3$.

In an actual device, the depletion region is, of course, not rectangular. Such a profile has been simulated using the MEDICI program[8] and is shown in Fig. 60.12. However, since the modulation depth depends only on the fundamental Fourier component of the shape of the depletion region, we expect the simulated results in Fig. 60.11 to closely approximate that of an actual device.

A similar structure has been used by Alferness and Buhl[9] on an electro-optic modulator, which provides the conversion between TE and TM modes. However, the co-directional coupling between TE and TM modes requires a much larger electrode period to satisfy the Bragg condition. As a result,

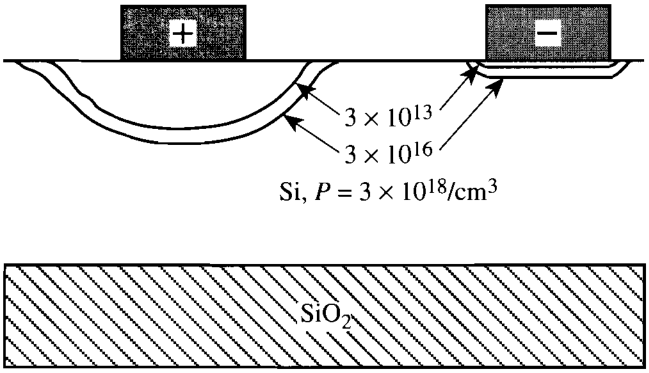

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Figure 60.12
The shape of the depleted region is examined by using the MEDICI simulation program. There are alternately depleted and undepleted regions under the reverse- and forward-biased finger electrodes. The finger width and spacing are 60 and 120 nm, respectively. The doping of silicon is $P = 3 \times 10^{18}/\text{cm}^3$; the bias voltage is 5 V.

the size of this TE ↔ TM modulator is large (of the order of millimeters). Furthermore, Alferness's modulator is not integrable with silicon planar circuits because an external polarizer is required to convert polarization modulation to intensity modulation.

The fabrication of our proposed modulator is feasible with existing fabrication techniques. Bond-and-etchback SOI wafers have proven to be a good optical waveguide material with scattering loss of about 3.3 dB/cm for $\lambda = 1.55\ \mu\text{m}$.[10] A grating coupler can be used to couple light into or out of the optical waveguide. The nanometer-sized finger electrodes can be fabricated by using modern electron-beam lithography.[11] A thin silicon-dioxide layer can be placed between the finger electrodes and the silicon layer to increase the breakdown voltage and avoid direct metal loading, which contributes to the attenuation of the guided wave.

The operational speed of this device is predominantly limited by the intrinsic device RC time constant, where R is the line impedance connecting to the modulator and C is the modulator capacitance. Parasitic capacitance for this structure is negligible, as shown from our previous measurements on a photodetector with similar structure.[11] For the inherent RC time constant, there is a trade-off between the modulation depth and the interaction length of the modulator, which affects its bandwidth. A modulator with 60-nm finger width, 120-nm finger spacing, 3-μm finger length, and 300-μm interaction length is calculated to have a capacitance of 0.22 pf.[12] (For the interdigitated structure, the capacitance is proportional to the interaction length and inversely proportional to the finger period.) If a microstrip line with 10-Ω impedance is used, the bandwidth of this modulator is $1/2\pi$ RC, or about 70 GHz. A thinner guiding layer may improve the bandwidth in two ways: by increasing the coupling constant, thus allowing a shorter interaction length, and by increasing the guided wavelength; as a result, the period of the metal fingers is increased and the capacitance is decreased.

For practical applications, the insertion loss to this modulator should be considered but is dependent on the configuration chosen. Free-carrier absorption would also contribute to the loss. For the proposed sample device, this effect is estimated to be about 0.6 dB[2]. Finally, for this Bragg reflector, an optical isolator such as a directional coupler at the insertion point is clearly necessary to prevent multiple reflections.

In conclusion, an ultrafast, all-silicon, light-intensity modulator has been proposed. An electric-field-induced Bragg reflector efficiently converts the small refractive-index modulation to light-intensity modulation. A modulator with 300-μm interaction length is shown to have a modulation depth about 40% with 5-V bias. Because it is a field-effect device, it has power dissipation dominated by leakage current and the resistance of the metal fingers. The speed of the modulator is limited only by the RC time constant, and a sample device has a bandwidth about 70 GHz. The same interdigitated structure has been demonstrated by us[13] to be usable as a picosecond photodetector. Both device structures are compatible with silicon circuits, lending themselves to potential use in integrated electronic-optoelectronic systems.

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