High-modulation-depth and short-cavity-length silicon Fabry–Perot modulator with two grating Bragg reflectors

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We propose a silicon Fabry–Perot planar waveguide modulator structure consisting of two Bragg reflectors to form the cavity. The Bragg reflectors are nanoscale trenches in the waveguide fabricated using electron beam lithography and reactive ion etching. Compared to conventional waveguide modulator designs, large modulation depth can be achieved with much smaller modulator length using high-finesse Fabry–Perot cavity, leading to much less loss and higher speed. This modulator design can also be utilized as an externally tunable spectral filter. © *1996 American Institute of Physics.* [S0003-6951(96)04702-6]

Optical modulators in silicon can have a strong impact on future optoelectronic integrated circuits, high-speed optical communication, optical interconnects, and optoelectronic signal processing systems.[1] It has been demonstrated that light with 1.3 and 1.55 μm wavelength can be waveguided in Si, and some modulator structures were also proposed and investigated.[2,3] Since crystalline Si does not have a strong electro-optic effect, Si modulators have to utilize the charge-carrier effect.[4] The refractive index change induced by charged carriers is very small, typically 10^{-3} at a carrier concentration change of 10^{18} cm^{-3}, which results in either a very long interaction length or a very small modulation depth. A modulator design based on Fabry–Perot (F-P) cavity was proposed to reduce the total modulator length and improve the modulation depth.[5] However, the two reflectors of the F-P resonator were semiconductor–air interfaces with a low reflectivity. The F-P cavity, therefore, has a low finesse; and a relatively long ($\sim$100 μm) modulator length is still required to achieve a reasonable modulator depth ($\sim$60%).[6] Others have also made F-P waveguide modulator with deposited mirrors or in different materials.[7,8] In this letter, we propose a new Si waveguide F-P modulator structure consisting of two Bragg waveguide reflectors. This modulator structure has small size, large modulator depth, and potential high speed.

The key concept of the new modulator design is to use two high-reflectivity lateral Bragg reflectors, fabricated on silicon-on-insulator (SOI) substrate using nanolithography and anisotropic etching. Figure 1 shows the schematic of the modulator. The two lateral Bragg reflectors consist of periodic quarter-wave trenches. The number of the trenches and the trench depth will determine the reflectivity of the Bragg reflectors, therefore, the finesse of the F-P cavity. By using high-reflectivity Bragg reflectors, a high-finesse F-P cavity can be formed and only a very small phase change in the cavity will be needed to achieve a large intensity modulation. The phase change is achieved utilizing the charge-carrier effect in Si; i.e., a change of charge-carrier concentration will change the index of refraction. To change the carrier concentration in a silicon waveguide, many different mechanisms have been proposed,[9] most are based on carrier injection or depletion and accumulation of the carriers at oxide–silicon interface in a metal-oxide-semiconductor field-effect transistor (MOSFET). The MOSFET implementation makes the fabrication process very compatible with the modern-day CMOS technology, and there is no static power dissipation because the control gate essentially draws no dc current. This is a very important factor for applications in large-scale optoelectronic integrated circuits.

In a conventional modulator consisting of two polarizers and an electro-optic material, the intensity modulation depth is equal to $\sin^2(\delta/2)$, where δ is the optical phase shift. An optical path change of $\lambda/2$ (phase shift of 180°) is needed to achieve 100% intensity modulation. For a carrier concentration change of 10^{18} cm^{-3}, the corresponding refractive index change is about 0.001, this requires a modulator length of about 1 mm, which is too big for large-scale integration and results in a big loss in the waveguide and a slow speed due to a parasitic elements of such long devices.

On the other hand, when near its resonance, the intensity transmittance of a high-finesse F-P cavity is very sensitive to small phase change. The intensity modulation depth depends strongly on the finesse (or end mirror reflectivity) and the length of F-P cavity. Figure 2 shows the dependence of the modulation depth on the reflectivity, when the refractive index change in the cavity is 0.001. We can see that to achieve a certain modulation depth, the larger the reflectivity, the shorter the required cavity length. For a F-P cavity modulator

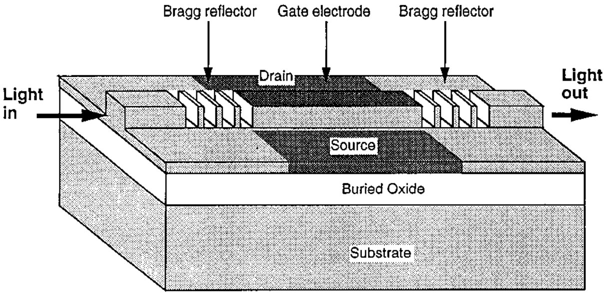

FIG. 1. Schematic view of the F-P waveguide modulator.

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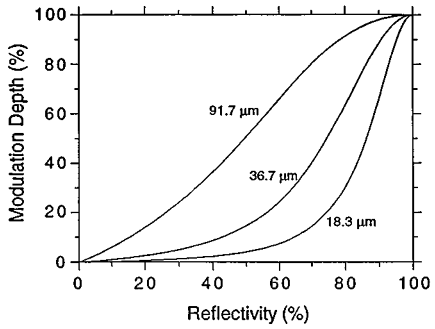
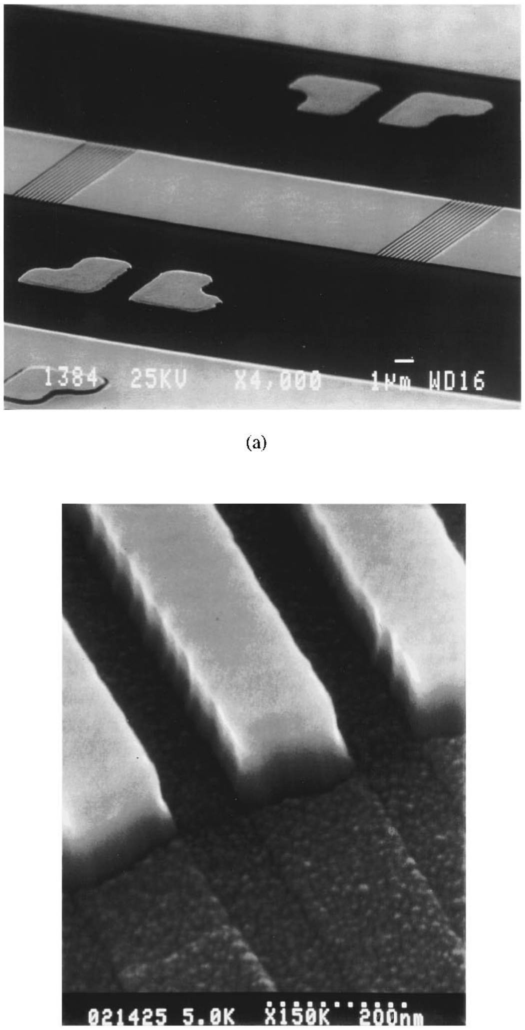


FIG. 2. Modulation depth vs reflectivity of the two mirrors of the F-P cavity for different cavity lengths.

with 98% reflectivity mirrors, an optical path change of λ/70 will change the transmittance of the cavity from 100% to 1%. At 1.3 μm wavelength, with the same charge-carrier injection level at 10^{18} cm^{-3}, only 18.3 μm long active region is needed. When compared to a conventional waveguide modulator that has millimeter size, the high-finesse F-P cavity structure greatly reduces the modulator size, leading to much less loss and faster modulator operation. We will show later that the Bragg reflector's reflectivity can be easily changed by varying the number of etched trenches; therefore, the design of such modulations is very flexible and it is easy to control and change the performance of the modulators.

The modulators are fabricated on SIMOX (separation by implanted oxygen) wafers. The top silicon layer thickness is 0.2 μm to ensure the single mode excitation in the SOI waveguide. The nanometer scale trenches on the waveguide were fabricated using electron-beam lithography and reactive ion etching (RIE). A thin SiO_2 layer was first thermally grown on the SOI wafer. Then a layer of polymethlymethacrylate (PMMA) was coated, exposed by direct electron beam writing, and developed. The electron-beam lithography system custom built in our laboratory can readily define patterns with 10 nm resolution.[10] The patterns in developed PMMA were transferred onto SiO_2 by fluorine-based RIE. Finally, chlorine-based RIE was performed to etch the trenches in the silicon waveguide while SiO_2 served as an etch mask. Scanning electron micrographs of a waveguide F-P cavity and a Bragg reflector with 12 trenches are shown in Fig. 3.

We used an effective refractive index model to calculate the reflectivity of the Bragg reflector.[11] The effective refraction indices for 0.2 and 0.1 μm thick planar waveguides at 1.3 μm wavelength are 2.83 and 2.25, respectively. Our model predicted a trench width 145 nm and a ridge width 115 nm, in order to form the Bragg reflectors. Figure 4(a) shows the relation between its reflectivity and the number of trenches. The 98% reflectivity is achieved only with 12 trenches. The reflectivity near the 1.3 μm wavelength is also shown in Fig. 4(b). Figure 5 shows the spectral transmittance of a modulator when the refractive index of the F-P cavity is changed by 0.001 due to change of the charged carrier concentration. The transmittance at 1.3 μm wavelength drastically reduces and the resonance peak shifts with the change of the refractive index. The modulator is very sensitive to the laser wavelength; therefore, it is not a spectrally broad modulator, and one must tune it to match the laser wavelength. On the other hand, this modulator can also be used as a tunable spectral filter, which is useful in the wavelength-domain multiplexing (WDM) and demultiplexing. A much narrower resonance peak and larger intensity modulation can be achieved when the Bragg reflectors have a higher reflectivity.



(a)

(b)

FIG. 3. Scanning electron micrographs of (a) a F-P cavity, and (b) a waveguide Bragg reflector. The width of the trench and the ridge is 145 and 115 nm, respectively.

The photon lifetime in the F-P cavity is an important factor to the response time and the bandwidth of the modulator. The photon lifetime depends on the reflectivity of the end mirrors and the length of the F-P cavity, as shown in Fig. 6, The smaller the reflectivity, or the shorter the cavity length, the faster the modulator can be. Another factor to the modulator speed is the time to change the carrier concentration. Since there are generally two ways to generate excess carriers in the cavity, the dominant factors to the modulator speed are different. For the field induced carrier accumulation or depletion, the limiting factor is the charging time of the control gate. In a MOS structure with 200 Å thick gate

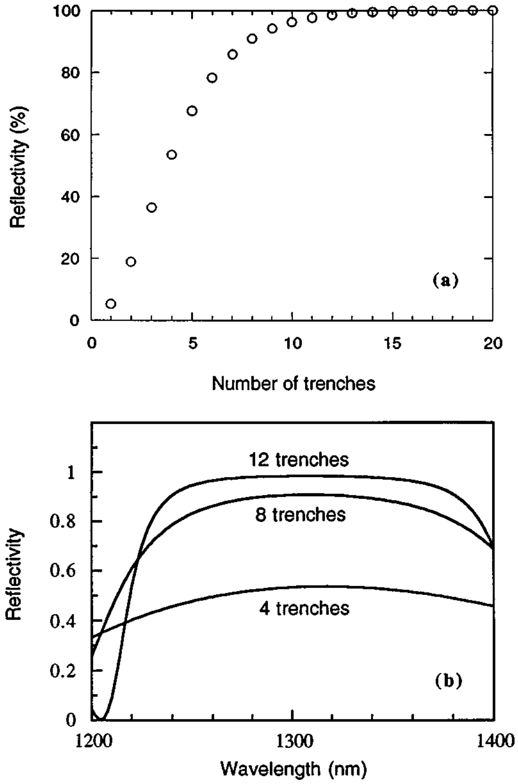


FIG. 4. The reflectivity of waveguide Bragg reflector vs (a) number of trenches and (b) wavelength. The waveguide thickness is 0.2 μm, trench depth is 0.1 μm. The width of the trench and the ridge is 145 and 115 nm, respectively.

oxide, the gate capacitance is 1.7 fF/μm^2. When the F-P cavity is 18.3 μm long and 10 μm wide and the impedance of the transmission line that charges the gate is 50 Ω, the R–C time is 15 ps. A narrower and shorter cavity will make the modulator faster. If excessive carriers are generated through injection from the source and drain region, the carrier transit time will become the limiting factor to modulator's speed. A narrow waveguide is preferred for high-speed modulator design. An approximate calculation indicates that to achieve a 15-ps carrier transit time across the waveguide, the waveguide width should be 1.5 μm if we assume that the carriers drift at a saturation velocity of 10^7 cm/s.

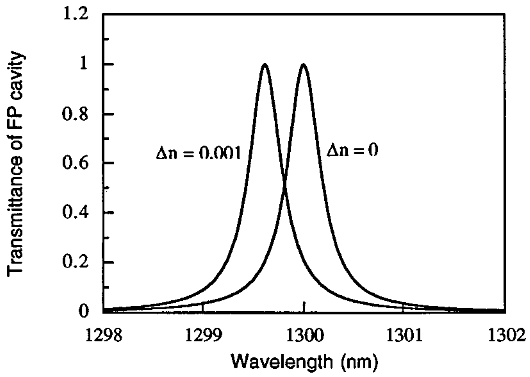


FIG. 5. The spectral transmittance of a modulator vs wavelength for two different refraction index changes. Each Bragg reflector has ten trenches, and the cavity is 18.3 μm long.

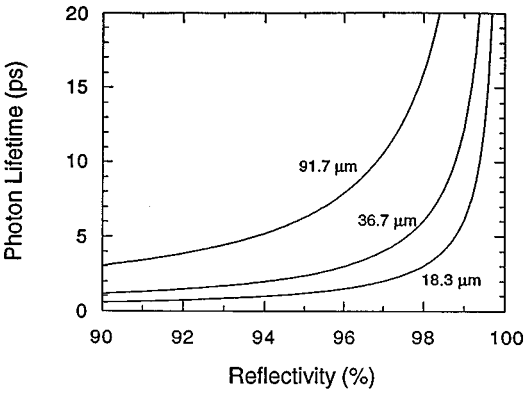


FIG. 6. Photon lifetime in F-P cavity vs the mirror reflectivity for different cavity lengths.

In summary, we have proposed a new Si waveguide modulator and have fabricated integrated Bragg reflectors in SOI using high-resolution electron beam lithography and reactive ion etching. Using high-finesse F-P cavity, large intensity modulation can be achieved with small modulator length. The design of the modulator is very flexible and the modulator performance can be easily tuned to meet the specific needs. Due to its small size, high speed, and compatibility with Si CMOS processes, this modulator structure is very promising for applications in future optoelectronic systems.

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