Operation and Optimization of Silicon-Diode-Based Optical Modulators

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Operation and Optimization of Silicon-Diode-Based Optical Modulators

Steven J. Spector, Cheryl M. Sorace, Michael W. Geis, Matthew E. Grein, Jung U. Yoon, Theodore M. Lyszczarz, Member, IEEE, Erik P. Ippen, Life Fellow, IEEE, and Franz X. Kärtner, Fellow, IEEE

(Invited Paper)

Abstract—An optical modulator in silicon based on a diode structure has been operated in both forward and reverse bias. This modulator achieves near state-of-the-art performance in both modes, thereby making this device ideal for comparing the two modes of operation. In reverse bias, the device has a $V_p L$ of 4.0 V·cm and a bandwidth of 26 GHz. In forward bias, the device is very sensitive, a $V_p L$ as low as 0.0025 V·cm has been achieved, but the bandwidth is only 100 MHz. A new geometry for a reverse-bias device is proposed, and it is predicted to achieve a $V_p L$ of 0.5 V·cm.

Index Terms—Diodes, integrated optics, optical communication, optical modulation, silicon-on-insulator (SOI) technology.

I. INTRODUCTION

One of the critical components for many silicon photonics applications is an electrooptic modulator. A large amount of research has been done investigating the use of various optical effects to achieve electrooptic modulation in silicon. The optical effects used in pure silicon systems include thermal [1], plasma dispersion [2], and the linear electrooptic effect in strained silicon [3]. Hybrid devices involving other active materials besides silicon have also been employed. These include modulators based on germanium/silicon heterostructures using the quantum confined Stark effect [4], and the Franz–Keldysh effect [5], III–V material bonded to silicon [6], and electrooptic polymer applied to a silicon slot-waveguide [7]. A large number of modulators using plasma dispersion have been demonstrated, and this is perhaps the most mature of these technologies. To use plasma dispersion for a modulator, a mechanism is necessary to affect the concentration of free carriers in a waveguide. This has been achieved in a number of ways. In a p-n diode under reverse bias, the depletion width can be modulated [8]–[11], removing free carriers. In a p-i-n diode, free carriers can be injected under forward bias [12]–[14]. In a MOS capacitor, the field effect can alter the accumulation of free carriers under a gate oxide [15].

The critical characteristics for a modulator are its sensitivity to applied voltage and high-frequency response. The measurement and optimization of these characteristics as well as the optical loss will be discussed for a diode-based modulator.

Table I summarizes the results of the best diode-based carrier-dispersion devices currently demonstrated in the literature. Some devices employ phase shifters in either resonant rings [12] or disks [10], and some devices use phase shifting waveguides in a more traditional Mach–Zehnder interferometer arrangement. Modulators using slow-wave structures have also been demonstrated [16], but these have not yet achieved the performance of the devices listed in the table. For Mach–Zehnder-interferometer-based devices, the standard figure of merit of $V_p L$ is listed. Since forward-bias diodes are current driven devices, this figure of merit is only a gauge for comparison with reverse-bias diodes. Nevertheless, the low $V_p L$ of the forward-bias devices does reflect the much greater sensitivity of these devices relative to reverse-bias devices. For devices that use resonant enhancement, a standard figure of merit is not available. The voltage required to switch the devices is listed, as defined by the respective authors. This voltage is determined by a number of characteristics of the device, including device quality factor ($Q$), ring diameter, and the performance with respect to carrier injection of the phase shifter.

For some devices in the literature, the speed or bandwidth has been directly measured, and the measured value is listed in the table. Often authors focus on digital performance, and in those cases only the speed of the device in bits per second is stated. This performance parameter is listed in the table, when the bandwidth of the device is unavailable. Often the bandwidth can be estimated to be greater than half the bit rate, for the nonreturn-to-zero (NRZ) scheme used in all the devices listed here. However, in many of these examples, in particular, for those devices that use forward-bias approaches, preemphasis is used to compensate for the bandwidth limitations of the device. The bandwidths of these devices are not simple to estimate from the available data. Note that the voltages listed are the peak-to-peak voltages of the signal into the device after preemphasis.

Because of the different metrics used by different authors, it is challenging to directly compare the different performance of the devices. The last two rows in the table represent the results of this paper’s authors, i.e., a single device that is operated in both forward and reverse bias. This device has achieved performance...
TABLE I

SUMMARY OF PREVIOUSLY DEMONSTRATED SILICON DIODE MODULATORS

<table>
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<tr>
<th>Author</th>
<th>Type</th>
<th>Speed</th>
<th>Sensitivity</th>
</tr>
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<tbody>
<tr>
<td>Liao (Intel Corp.) [8]</td>
<td>Reverse Bias PN Mach-Zehnder</td>
<td>30 GHz</td>
<td>4 V·cm</td>
</tr>
<tr>
<td>Xu (Cornell) [12]</td>
<td>Forward Bias P-i-N</td>
<td>12.5 Gb/s</td>
<td>16 V</td>
</tr>
<tr>
<td>Ring Resonator</td>
<td></td>
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<tr>
<td>Green (IBM) [13]</td>
<td>Forward Bias P-i-N</td>
<td>10 Gb/s</td>
<td>0.036 V·cm, 7 V</td>
</tr>
<tr>
<td>Mach-Zehnder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marris-Morini (Université Paris) [9]</td>
<td>Reverse Bias PN Mach-Zehnder</td>
<td>10 GHz</td>
<td>4 V·cm</td>
</tr>
<tr>
<td>Watts (Sandia Nat. Labs.) [10]</td>
<td>Reverse Bias PN Disk Resonator</td>
<td>10 Gb/s</td>
<td>3.5 V</td>
</tr>
<tr>
<td>Zhou (MIT) [14]</td>
<td>Forward Bias PN Mach-Zehnder</td>
<td>100 MHz</td>
<td>0.0025 V·cm</td>
</tr>
<tr>
<td>Spector (MIT Lincoln Laboratory) [11]</td>
<td>Reverse Bias PN Mach-Zehnder</td>
<td>26 GHz</td>
<td>4 V·cm</td>
</tr>
</tbody>
</table>

Speeds in gigahertz correspond to 3 dB bandwidth, and those in gigabits per second correspond to the highest bit rates achieved by the author. The sensitivities are reported in volts centimeters, if available. The peak-to-peak drive voltage used to achieve the given bit rate is also listed, if available.

roughly equivalent to that of the best devices in the current literature, for both modes of operation. Analysis of this modulator will provide a detailed and direct comparison between these two modes of operation. In forward bias, a $V_{πL}$ of 0.0025 V·cm was achieved with 100 MHz of bandwidth. In reverse bias, $V_{πL}$ was 4 V·cm with 26 GHz of bandwidth. Although this is very good performance for a p-n diode modulator under reverse bias, further optimizations of the design are possible. An improvement to the design is proposed that is projected to achieve 7× better sensitivity and a $V_{πL}$ of 0.5 V·cm.

II. METHOD

A. Device Description

The modulators are fabricated using Unibond silicon-on-insulator (SOI) wafers with a 0.22-µm-thick layer of silicon above a 3-µm buried oxide. Fig. 1(a) schematically shows the top view of the modulator. The active areas of the device are p-n diode phase shifter sections in the arms of the modulator. By employing a relatively short interaction length (typically 0.5 mm), a simple lumped element electrode can be used. The modulator can be operated in a push–pull configuration by driving the center electrode (as shown), or a single arm can be driven. An additional thermal phase shifter (not shown) is fabricated on one arm to allow the modulator to be driven at quadrature, regardless of the bias on the diodes.

Fig. 1(b) shows schematically the cross section of the waveguide in the active area of the modulator. The central region, or core of the waveguide is 220 nm thick, 500 nm wide, and lightly n-type-doped to a concentration of $2 \times 10^{17}$ cm$^{-3}$. The sidewalls are moderately doped, n-type on one side and p-type on the other, to a concentration of $10^{18}$ cm$^{-3}$ and an approximate depth of 50 nm. When a reverse bias is applied, a depletion region forms at the p-n junction on one side of the waveguide. This depletion region’s size increases into the center of the waveguide as the bias is increased, thus creating a change in the refractive index of the waveguide. Under forward bias, carriers are injected from both sides of the diode, increasing the number of carriers in the lightly doped n-region in the center. The device acts nearly identically to a p-i-n diode under forward bias; the lightly doped n-region in the center has little effect. To make electrical contact to the core of the waveguide, 50-nm-thick slab regions (heavily doped, $10^{19}$ cm$^{-3}$ concentration), the waveguide is connected to metal contacts located 1 µm away. To ensure good ohmic contact, the silicon slab under the metal contacts is degenerately doped to a concentration of $10^{21}$ cm$^{-3}$. The parasitic resistance of the diodes including ohmic contacts and the resistance of the doped Si is usually <0.3 Ω·cm.

An adiabatic output coupler [11], [17], instead of the more standard y-coupler, is used to combine the two arms of the Mach–Zehnder interferometer. This type of output coupler provides low loss, broadband functionality, and two complementary outputs (channels 1 and 2) from the modulator. The two complementary outputs can be used in analog applications to linearize the transfer function of the modulator and to compensate for fluctuations external to the modulator [18], [19]. To provide

Fig. 1. (a) Top-view layout of the dual-output Mach–Zehnder modulator. (b) Schematic view of the cross section of one of the phase shifters (all dimensions are in micrometers).
efficient coupling on and off the wafer, reverse taper couplers combined with lower index oxynitride waveguides [20] are used.

B. Testing Method

For the frequency response measurements, the modulator is driven in a push–pull configuration. A 1550-nm laser beam generated by a laser diode with maximum optical power of $\sim 10$ mW is coupled into the modulator via a lensed fiber. A fiber polarization controller is used to match the polarization of the input laser to the silicon waveguide. After coupling losses and other losses, about 1 mW of optical power is estimated to enter the modulator. The RF signal is generated by a network analyzer and connected to the modulator chip through a bias tee. RF powers of approximately 1 mW were used. The output beam from the modulator chip is collected by an aspheric lens, goes through a fiber preamplifier, a 2-nm bandpass filter, another fiber amplifier, and is then finally detected with an $\sim 50$-GHz InGaAs photodetector. The configuration used to make dc measurements is similar, but a number of modifications are made. For the dc measurements, the modulator is driven using a single arm. Instead of the network analyzer and bias tee, a dc power supply is used to operate the modulator. The fiber amplifier was no longer used, and an optical power meter replaced the high-speed photodetector.

III. EXPERIMENTAL RESULTS

A. DC Characteristics

The dc response of a 0.5-mm-long modulator operated in forward bias is plotted in Fig. 2. The response is plotted as a function of the current in the device. The output of channel 1 has a decaying sinusoidal response, with the first peak occurring at a voltage of 0.9 V and 1 mA, and the first minimum occurring at 1.0 V and 5.5 mA. This gives a $V_{\pi}$ of 0.1 V, or a $V_{\pi}L$ of 0.005 V-cm. Although $V_{\pi}L$ is a standard metric for comparing phase shifters, $V_{\pi}L$ is not a good metric for characterizing phase shifter performance when operating in forward bias. A good universal metric should treat changes in device length or applied voltage equivalently. However, in forward bias, the number of free carriers in the device depends primarily on the current in the device and the voltage is clamped at the knee voltage of the diode. Because the $I$–$V$ curve for a diode in forward bias is exponential, a small change in voltage has a much larger impact on $V_{\pi}L$ than a small change in $L$. One can then lower $V_{\pi}L$ significantly by making the device as short as possible and making the incremental increase in $V$ necessary to compensate. This works over the exponential range of the $I$–$V$ characteristic until the series resistance in the diode starts to dominate. A device 0.25 mm long was tested and had roughly the same performance as the 0.5 mm device giving a $V_{\pi}L$ of 0.0025 V-cm. A better metric for the performance is the signal power required to drive the device between minimum and maximum transmission. In this case, the average power for a 50% duty cycle square-wave signal is $(V_{\pi}/2)(5.5–1)$ mA = 0.22 mW. It also should be noted that the response (i.e., the amount of index change) of the device is not linear with current or voltage. The spacing between subsequent maxima and minima increases with current. Both complementary outputs are shown in Fig. 2, and the second channel has the expected inverted shape of the first channel, i.e., the second channel goes low, when the first channel goes high, and vice versa. Both channels show a decaying signal as the current increases due to the increased absorption from the greater number of free carriers in the device. The best extinction achieved is 20 dB.

The dc response of a 5-mm-long modulator operated in reverse bias is plotted in Fig. 3 with the response plotted as a function of voltage. Unlike the shorter device shown earlier, the extinction achieved is only 4 dB. The poor extinction may indicate that there is uneven loss in the two long arms of the modulator. The spacing between the first peak at 3 V and the minimum at 11 V give a $V_{\pi}$ of 8 V, or a $V_{\pi}L$ of 4 V-cm. As in the forward-bias case, the response of the device is not linear (with voltage). This is expected, since the width of the depletion region scales roughly as the square root of voltage. Very little dc current is needed to operate the device in reverse bias. There is a small amount of dc current (about 1 $\mu$A) that depends on the intensity of light in the waveguide. This is believed to be photocurrent generated by defects states, most likely in the sidewalls of the waveguide [21].
B. RF Characteristics

The ac response of the same 0.5-mm-long device operated in forward and reverse bias is shown in Fig. 4. The bias voltage in forward bias is 1 V, and the bias voltage in reverse bias is 16 V. As can be seen from the graph, forward-bias operation is much more sensitive than reverse bias at lower frequencies. However, the forward-bias operation is limited by the carrier lifetime [14]. Its 3 dB response point is near 100 MHz. Conversely, reverse-bias operation, which is not limited by the carrier lifetime, has excellent bandwidth with a 3 dB point near 26 GHz. At smaller reverse biases, the response changes only a little. At a reverse bias of 2 V, the bandwidth decreases to 20 GHz, due to an increase in the capacitance, but the sensitivity increases by 2.5 dB. The response curves of the forward and reverse bias (at 16 V) modes of operation cross at 13 GHz. It has been shown that reducing the carrier lifetime can improve the bandwidth of the device when operated in forward bias [14]. The response of a similar device that had its carrier lifetime reduced, by silicon implantation (with an area dose of 1 × 10^{14} cm^{-2} and energy of 190 keV) is also plotted in Fig. 4. Although the implantation did improve the bandwidth of the device to 1 GHz, this increase in bandwidth was at the expense of the sensitivity at lower frequencies. At frequencies above 5 GHz the devices with and without the Si implantation perform nearly identically. The silicon implantation also increases the loss of the waveguide by about 100 dB/cm. It may be possible to reduce the carrier lifetime without such losses by tailoring the energy of the implant [22].

IV. MODELING AND OPTIMIZATION

A. Forward Bias

The forward-bias response of the device was modeled previously in [14]. In that work, a numerical model using SENTAUROUS (Synopsis) software was used to predict the performance of the device, and the predictions showed very good agreement with the experimental performance. There is little that can be done to further improve the performance of the device in forward-bias operation. Modeling and experiments have both shown that decreasing the carrier lifetime improves the bandwidth, but the sensitivity at higher frequencies does not actually increase. Fundamentally, the phase change in the modulator depends on the carriers being driven into the device and the time it takes for the carriers to leave. At frequencies slower than the carrier lifetime, the carrier concentration can reach steady state. At these frequencies, the maximum number of carriers in the device will depend on the carrier lifetime. A shorter lifetime will lead to a smaller number of carriers, thereby reducing sensitivity. However, a shorter lifetime will improve the bandwidth, because the carriers can reach steady state at a higher frequency. At frequencies much faster than the carrier lifetime, the carrier lifetime has no effect on the forward-bias response.

Small gains can be made by further shrinking the cross section of the device, so that less total charge is necessary for the same modal index change. There is a limit to how compact the mode can be before the index of silicon can no longer confine it. A simple model, where the charge injection is considered be constant over the cross-sectional area of the device, shows that a waveguide with dimensions of 400 nm × 150 nm is nearly optimal. The improvement is only modest, with 17% less charge necessary for the same modal index change compared to the fabricated device. Shrinking the device also may have the advantage of decreasing the carrier lifetime without greatly changing the loss of the device. Carrier lifetime generally scales with the size of a structure, because much of the carrier recombination occurs at the surface.

B. Reverse Bias

The dc response of the device in reverse bias has been modeled by solving Poisson and carrier continuity equations [11], and the model and measurements are in fairly good agreement. Although this device performs well, further optimizations to improve the sensitivity are possible. Replacing the n-type carriers with p-type in the center of the waveguide should improve the device response by nearly a factor of 2 due to the greater index change caused by p-type carriers at these concentrations [2]. A further improvement can be made by having a horizontal p-n junction rather than a vertical junction. Previously fabricated designs that use a waveguide with horizontal junction require an epitaxial overgrowth [8]. Another device has been demonstrated that has a horizontal junction in a disk [10]. In this device, the whispering gallery mode of the disk is used, allowing contact to be made in the center of the disk away from the mode. Fig. 5 shows a device that is simple to fabricate and use in a standard Mach–Zehnder and uses a primarily horizontal junction, and arrangement similar to [23], and [24]. To fabricate this device, the entire waveguide is doped p-type, and then the appropriate top part of the waveguide is counter doped n-type at a higher concentration. (The n-type doping does not extend over the entire top of the waveguide to allow for realistic alignment tolerances).

To optimize this device, different thicknesses and different p-type doping concentrations were modeled. Fig. 6 shows the performance as the rib height h is changed. To gauge the performance of the device, the index change when the voltage goes from 0 to 2 V was used as a metric. The optimal rib height
is found to be 150 nm (for a p-type carrier concentration of $6 \times 10^{17} \text{cm}^{-3}$). This height gives the best performance because the optical mode overlaps best with the depletion region.

Fig. 7 shows the performance as the p-type doping concentration is altered (with a rib height of 100 nm). For the range of p-type concentration modeled, the performance improves with increasing p-type concentration. This is expected, because the amount of depleted charge in a junction at a given voltage scales as the square root of the doping concentration [25]. However, as will be discussed in the next section, optical loss also increases with carrier concentration. For a reasonable tradeoff, a carrier concentration of $6 \times 10^{17} \text{cm}^{-3}$ was chosen for an optimum.

Fig. 8 shows the comparative responses of three modeled devices: the device shown in Fig. 1 (fabricated and tested above), a similar device with p-type carriers in the center, and an optimized version of the device shown in Fig. 5. The optimized device is much more sensitive particularly at low voltages. This device (with a rib height of 150 nm and p-type carrier concentration of $6 \times 10^{17} \text{cm}^{-3}$ in the center of the waveguide) achieves a $V_L L$ of 0.5 V·cm at low bias voltages. This is a $7 \times$ improvement over the original device that has a modeled $V_L L$ of 3.5 V·cm at low-bias voltages.

The capacitance of the device was modeled (also using SENTAURUS software) to be 4.9 pF/cm compared to 1.9 pF/cm for the older design. With a 50 $\Omega$ impedance from a power supply and a 700 $\mu$m device (necessary to achieve a $\pi$ phase shift in a push–pull configuration with $\pm 3$ V), the $RC$ time constant ($\tau_{RC} = RC$) is 17 ps, and the $RC$-limited bandwidth ($BW_{RC} = (2\pi \tau_{RC})^{-1}$) is nearly 10 GHz. To achieve higher bandwidth, a shorter device could be used, but less modulation depth would be achieved. Traveling-wave electrodes could also be employed to reduce the $RC$ time constant limitation [26].

### C. Optical Loss

The device described previously was optimized for sensitivity, but for some applications low loss may be more important. Because the same carriers that are necessary for index change cause absorption, any modulator that relies on plasma dispersion will intrinsically have some optical loss. The formulas used to relate carrier concentration to index change and optical loss at a wavelength of 1.55 $\mu$m are

$$\Delta n = \Delta n_e + \Delta n_h = -8.8 \times 10^{-22}$$
$$\Delta N_e - 8.5 \times 10^{-18}(\Delta N_h)^{0.8}$$ (1)
$$\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = 9.1 \times 10^{-22}$$
$$\Delta \alpha_e^{1.12} + 2.5 \times 10^{-20}\Delta N_h^{1.13}$$ (2)
where $\Delta n_e$ is the change in refractive index resulting from the change in free electron carrier concentrations, $\Delta N_e$, $\Delta n_h$ is the change in refractive index resulting from the change in free hole carrier concentrations, $\Delta N_h$, $\Delta \alpha_e$ and $\Delta \alpha_h$ are the changes in absorption resulting from $\Delta N_e$ and $\Delta N_h$, respectively, and $\Delta n$ and $\Delta \alpha$ are the net changes in refractive index and absorption, respectively.

The earlier modeling of the modulators used (1), which is a commonly used approximation to the data of Soref and Bennet [2]. It should be noted that (2) differs from the commonly used approximation for the optical absorption, because in this case, the approximation can result in substantial error. The nonlinear equation (2) is a power law fit to the data in [2] and follows the experimental data in [2] much more accurately.

For p-type dopants, the ratio of index change to loss ($\Delta n_h/\Delta \alpha_h$) is not constant with changes in $\Delta N_h$. As a first step in estimating the loss in a modulator, consider a phase shifter in bulk silicon with only p-type carriers. p-Type carriers are chosen because they give greater index change and less absorption than n-type carriers. The absorption versus carrier concentration in bulk p-type silicon is plotted in Fig. 9. This figure shows the amount of loss versus carrier concentration in enough silicon thickness for the carriers to cause a $\pi$ phase shift. Also plotted in this figure is the thickness of the silicon that gives a $\pi$ phase shift. As the concentration is lowered, the ratio of $\Delta n_h/\Delta \alpha_h$ improves and the optical loss goes down, but the length of the device required for a $\pi$ phase shift increases. In general, the optimization of loss will lead to less sensitive, longer devices with lower carrier concentrations. This is true even for devices that reach full depletion (i.e., no carriers within the mode at maximum reverse bias) during operation. Although full modeling of the losses in the devices described earlier has not been done, the best-performing devices have the highest carrier concentration and can be expected to have the highest optical losses.

Fig. 9 also provides an estimate of the minimum loss that can be achieved in a modulator. Lengths greater than a few centimeters are likely impractical for high-speed devices, limiting the loss to around 0.2 dB. Real devices will have other loss mechanisms, such as sidewall scattering, which will also limit how low the achievable optical loss is.

V. CONCLUSION

A modulator has been demonstrated that can be operated in forward and reverse bias, with performance similar to the best devices that have been demonstrated using either mode of operation. This device is ideally suited for making a direct comparison between these two modes of operation. In forward bias, the device is very sensitive ($V_L = 0.0025$ V-cm) but has low bandwidth (~100 MHz). In reverse bias, the device is much less sensitive ($V_L = 4$ V-cm), but has higher bandwidth (~26 GHz). The response curves of the two modes of operation cross at 13 GHz; below 13 GHz forward bias is more sensitive, while above 13 GHz reverse bias is more sensitive. For lower speed applications, a device that operates in forward bias may be preferred. The bandwidth of the forward-biased device can be extended by using a high-pass, preemphasis filter, or by lowering the carrier lifetime in the device. Both of these techniques create a flatter response by lowering the low-frequency response of the system.

Forward-bias phase shifters are already close to their fundamental limit in performance. Small improvements can be made by changing the geometry of the device, but dramatic improvements are unlikely. There is, however, room for improvement in reverse-bias devices. A new geometry for reverse-bias operation, using a horizontal junction, was proposed and optimized, and this device is modeled to have a $7 \times$ improvement in sensitivity. This improved reverse-biased device may be preferable over a forward-bias device for all but the lowest speed applications.

To achieve low optical loss in a modulator, a device that relies on p-type carriers at relatively low concentrations is best. Lower carrier concentrations, however, reduce sensitivity and increase device length. When designing a device, it may be necessary to tradeoff sensitivity for optical loss.

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