High-speed electrooptical VOA integrated in silicon-on-insulator

Qingfeng Yan (严清峰)[1], Jinzhong Yu (余金中)[1], Jinsong Xia (夏金松)[1], and Zhongli Liu (刘忠立)[2]

[1] *State Key Laboratory on Integrated optoelectronics, Institute of Semiconductors,*
Chinese Academy of Sciences, Beijing 100083
[2] *Microelectronics R&D center, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083*

Received December 5, 2002

In this paper, we present simulation results of an electrooptical variable optical attenuator (VOA) integrated in silicon-on-insulator waveguide. The device is functionally based on free carriers absorption to achieve attenuation. Beam propagation method (BPM) and two-dimensional semiconductor device simulation tool PISCES-II were used to analyze the dc and transient characteristics of the device. The device has a response time (including rise time and fall time) less than 200 ns, much faster than the thermooptic and micro-electromechanical systems (MEMSs) based VOAs.

OCIS codes: 130.0250, 250.7360.

Variable optical attenuators (VOA) are commonly used in wavelength division and multiplexing (WDM) systems to prove gain equalization in optical amplifiers, channel blanking for network monitoring and signal attenuation for detector saturation protection. A various of planar light-wave circuit VOAs that use the thermooptical effect and VOAs based on MEMS technology have been reported in the literatures[1,2]. However, the response speed of these devices is slow and limited approximately to 1 ms.

In this paper, we present a VOA integrated in silicon-on-insulator (SOI) waveguide. The device utilizes a p-i-n structure to inject charge into the silicon waveguide. Charge injection into the silicon changes both the refractive index and linear absorption coefficient of the material due to the free carriers dispersion effect (also called plasma dispersion effect). Thus an electrical signal can be used to attenuate the light propagating inside the waveguide. The response of this type of VOA is very fast since electrooptic modulation is much faster than thermooptic modulation and mechanical operation.

The schematic of the VOA in SOI is shown in Fig. 1. It consists of a single mode SOI waveguide with two tapered access waveguides, which can couple efficiently with input or output fibers. A p-i-n structure is integrated into the single mode SOI rib waveguide for implementation of free carriers injection. Figure 2 shows the cross section of the active region. A lateral N$^+$-I-P$^+$-I-N$^+$ structure is implemented by loading the P$^+$ doped region at the top of the rib waveguide and the two N$^+$ doped regions at each side of the rib waveguide.

As we know, unstrained pure crystalline silicon is transparent in the near infrared (1.3−1.5 μm) and lightly doped silicon exhibits less than 0.1 dB·cm^{-1} of intrinsic optical absorption. This is one of the important reasons why silicon becomes a significant material for optical applications. To acquire optical amplitude modulation or optical signal attenuation, it is demanded to change the optical absorption coefficient of silicon. The most effective and practical mechanism for varying the absorption coefficient of light in pure silicon is the free carriers plasma dispersion effect[3]. According to plasma dispersion effect, at a free space wavelength $\lambda = 1.55$ μm, the change in optical absorption coefficient as a function of free electron and free hole concentration can be obtained by[4]

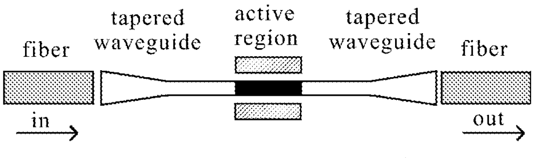

Fig. 1. Schematic of electrooptical VOA in silicon-on-insulator.

$$\begin{aligned}\Delta\alpha &= \Delta\alpha_{\mathrm{e}} + \Delta\alpha_{\mathrm{h}} \\ &= 8.5\times10^{-18}\cdot\Delta N_{\mathrm{e}} + 6.0\times10^{-18}\cdot\Delta N_{\mathrm{h}}, \qquad (1)\end{aligned}$$

where $\Delta\alpha_{\mathrm{e}}$ is the change in optical absorption coefficient due to change in free electron concentration, $\Delta\alpha_{\mathrm{h}}$ is the change in optical absorption coefficient due to change in free hole concentration, ΔN_{e} is the change of free electron concentration, and ΔN_{h} is the change of free hole concentration.

From Eq. (1), we can see that a change in the optical absorption coefficient in silicon can be achieved by means of free carriers injection of both electrons and holes into the intrinsic region with a forward biased silicon p-i-n diode. Thus, variable optical attenuation can be achieved by applying various forward biases on p-i-n structure integrated in SOI waveguide.

Using the first order perturbation theory, the effective optical absorption coefficient change $\Delta\alpha_{\mathrm{eff}}$ for a waveguide mode is given by[5]

$$\begin{aligned}\Delta\alpha_{\mathrm{eff}} = &\frac{1}{\alpha_{\mathrm{eff}}^{(0)}} \\ &\cdot\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Delta\alpha(x,y)\cdot\alpha_0(x,y)|E^{(0)}(x,y)|^2\mathrm{d}x\mathrm{d}y\right) \\ &/\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E^{(0)}(x,y)|^2\mathrm{d}x\mathrm{d}y\right), \qquad (2)\end{aligned}$$

where $|E^{(0)}(x,y)|^2$ is the optical intensity profile, $\alpha_0(x,y)$ is the intrinsic absorption coefficient distribution in the waveguide structure, $\Delta\alpha(x,y)$ is the local absorption coefficient change due to free carriers injection and $\alpha_{\text{eff}}^{(0)}$ is the effective absorption coefficient of the mode in the absence of injection. Since the absorption coefficient change is significant only in the central n^--Si waveguiding region, Eq. (2) can be simplified as

$$\Delta\alpha_{\text{eff}} = \frac{\alpha_{\text{Si}}}{\alpha_{\text{eff}}^{(0)}} \cdot \overline{\Delta\alpha} \cdot \Gamma, \tag{3}$$

where

$$\Gamma = \frac{\left[\iint\limits_{\text{CW}} |E^{(0)}(x,y)|^2 \mathrm{d}x\mathrm{d}y\right]}{\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E^{(0)}(x,y)|^2 \mathrm{d}x\mathrm{d}y\right]}, \tag{4}$$

is the confinement factor of the optical field in the waveguide and

$$\overline{\Delta\alpha} = \frac{\left[\iint\limits_{\text{CW}} \Delta\alpha(x,y)\cdot|E^{(0)}(x,y)|^2 \mathrm{d}x\mathrm{d}y\right]}{\left[\iint\limits_{\text{CW}} |E^{(0)}(x,y)|^2 \mathrm{d}x\mathrm{d}y\right]}, \tag{5}$$

is the average absorption coefficient change in the central waveguiding region. For the convenience of simulation, we suppose $\Gamma = 1$ and $\alpha_{\text{Si}} = \alpha_{\text{eff}}^{(0)}$, from which we get $\Delta\alpha_{\text{eff}} = \overline{\Delta\alpha}$.

Figure 3 shows the simulated fundamental mode distribution of the single mode SOI wavegide with beam propagation method (BPM), in which the N$^+$-I-P$^+$-I-N$^+$ structure is implemented. To load only single mode, the waveguide has a width of 4 μm and a height of 5 μm, the etch ratio of the rib waveguide is 0.65 which results in a rib height of 3.25 μm. By using the two-dimensional (2-D) semiconductor device simulation tool PISCES-II, the injected free carriers distribution inside the central waveguide region can be obtained when a given forward bias is applied on the p-i-n structure, which will consequently result in the profile of absorption coefficient change. From Eq. (5), maximum attenuation can be acquired by optimizing the interaction between the change in absorption coefficient and the optical mode in the central waveguide.

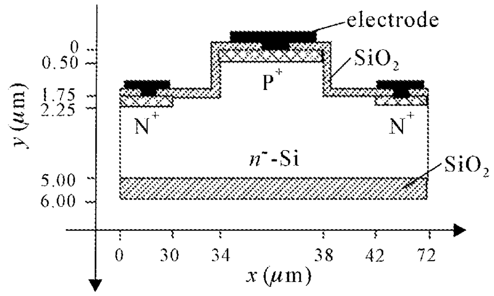

Fig. 2. Cross-section of the active region.

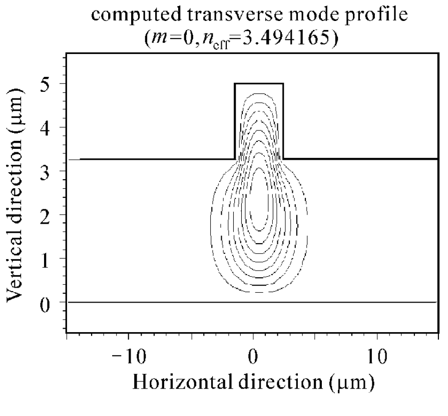

Fig. 3. Fundamental mode distribution in the SOI single mode wavegide.

In this paper, PISCES-II is used to predict the injected free carriers densities in the intrinsic region of the modulation area, as well as the dc behavior and the response characteristics of the electrooptical VOA. For N$^+$-I-P$^+$-I-N$^+$ structure presented in this paper, the P$^+$ doping concentration is 4×10^{19} cm^{-3} and a N$^+$ doping concentration is 5×10^{19} cm^{-3}. The width of the P$^+$ and N$^+$ doping area is 4 and 30 μm, respectively. The doping depth of P$^+$ region and N$^+$ region is 0.5 μm. The distance between the P$^+$ section and the two N$^+$ sections is 4 μm. The length of the active region is 10000 μm. The device was modeled assuming ohmic contacts with no additional contact resistance or capacitance. Supposing the n^--Si guiding layer has a doping concentration of 1.11×10^{15} cm^{-3}, according to Ref. [5], we assume the Shockley-Reed-Hall recombination carrier lifetime in the intrinsic region to be $\tau_{\text{n}} = 700$ ns and $\tau_{\text{h}} = 300$ ns, where τ_{n} is the electron lifetime and τ_{h} is the hole lifetime. At high levels of injected carriers concentration, Auger recombination and carrier-carrier scattering in the intrinsic region have to be taken into account. So, the model is constructed including several carrier mobility mechanism and recombination mechanisms simultaneously.

The optical attenuation at various applied electrical power on the VOA is illustrated in Fig. 4. It can be seen the attenuation is sub-linear with the applied electrical power, though the absorption coefficient is linear with the carriers concentration according Eq. (1). The reason is that at high level of injection electrical power the Auger combination and the scattering between carriers enhance, which will decrease the efficiency of plasma dispersion. To acquire higher attenuation, much higher injection electrical power is needed.

To investigate the response characteristics of the VOA, a transient solution was used. Figure 5 shows the response characteristics of the VOA operating at 5-dB attenuation. The VOA is initially biased at 5-dB attenuation, and then additional 0.5-dB peak attenuation square signal is loaded. Defining the 10% – 90% peak attenuation time as the rise time and the 90% – 10% peak attenuation time as the fall time. It can be seen the device operating at 5-dB attenuation has a 33.4 ns rise time and 149.9 ns fall time and the total response time is 183.3 ns. Similarly, the response time at other attenuation can be modeled.

Figure 6 shows the total response time of the VOA at different attenuations. It can be seen clearly that the total response time decreases with the increase of the attenuation. At higher level of bias attenuation, the

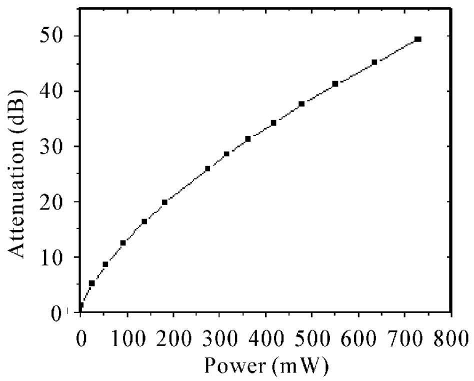

Fig. 4. Attenuation versus applied electrical power.

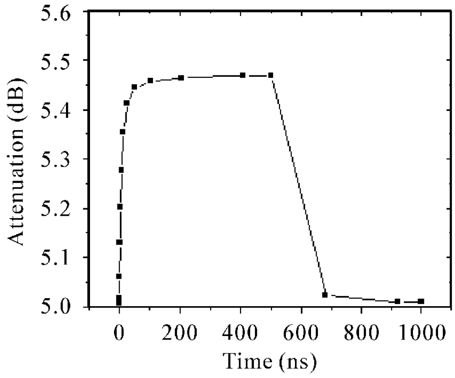

Fig. 5. Response characteristics of the VOA at 5-dB attenuation.

free carriers generation and recombination rate increases, thus the lifetime of the free carriers decreases. Since the modulation speed is directly correlated with the free carriers lifetime, this consequently causes the effect as Fig. 6 illustrates. Moreover, Fig. 6 also shows that the total response time of the electrooptical VOA is less than 200 ns, much faster than other thermooptic or MEMS based VOA.

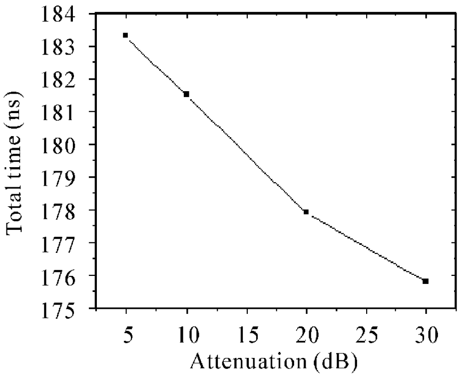

Fig. 6. Total response time of the VOA at different attenuations.

In conclusion, we have demonstrated the electrooptical VOA integrated in silicon-on-insulator. The device is functionally based on the free carriers dispersion in silicon. The dc and transient characteristics of the device was simulated via BPM and 2-D semiconductor device simulation tool PISCES-II. The results show the VOA has a total response time less than 200 ns, much faster than the thermooptic or MEMS based VOAs reported.

This work was supported by the National Natural Science Foundation of China under Grant Nos. 69896260 and 69990540, and the "973" Project by the National Science and Technology Ministry under Contract No. G20000366. Q. Yan's e-mail address is qfyan@red.semi.ac.cn.

References

1. S. S. Lee, J. U. Bu, S. Y. Lee, K. C. Son, C. G. Park, and T. S. Kim, IEEE Photon. Technol. Lett. **12,** 407 (2000).
2. X. M. Zhang, A. Q. Liu, C. Lu, and D. Y. Tang, Electron. Lett. **38,** 382 (2002).
3. R. A. Soref and B. R. Bennett, IEEE J. Quantum Electron. **23,** 123 (1987).
4. P. D. Hewitt and G. T. Reed, J. Lightwave Technol. **18,** 443 (2000).
5. A. Vonsovici and A. Koster, J. Lightwave Technol. **17,** 129 (1999).