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Silicon Electro-Optic Modulator Fabricated on Silicon Substrate Utilizing the Three-Terminal Transistor Waveguide Structure

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INTRODUCTION

Our contemporary generations have all witnessed and also at the same time enjoyed the benefits of a revolutionary advancement in silicon microelectronics for the last century. It is foreseeable that the very blessings endowed by the silicon-related technologies are expected to expand in a much greater scale if silicon-based materials can be put into good uses for integrated photonics applications. In fact, the recent development in silicon-based photonics has transcended to such a level that witnessing the large scale integration between electronic and photonic device components on silicon substrates such as optoelectronic integrated circuits (OEICs) thus becomes highly possible in a near future. In fact, the progress in silicon photonics has steadily picked up its pace since early 1990s and a number of commercial-grade silicon-based OEICs such as transceivers operating in the fiber optics communication wavelengths (1.31 – 1.55 μm) have already entered the market. Part of reasons for the successes of "silicon revolution" in microelectronics and photonics is due to the fact that silicon is a robust material for passive and active optoelectronic device applications in the infrared regime (λ > 1.2 μm) of the electromagnetic spectrum. It is needless to say that a lot of works have already demonstrated that the infrared light can be guided [1], detected [2], emitted [3], modulated and switched [4] in silicon and its related compounds. In particular, being able to effectively modulating and switching light signal in silicon is of vital importance for device applications in fiber optics communications. In fact, one of most crucial figures of merit to characterizing an optical modulator is the modulation depth. It is well-known that the modulation of a silicon modulator can only be achieved via the thermal-optic and free-carrier plasma dispersion effects. From the perspective of improving switching characteristics, the plasma dispersion or carrier injection effect is often employed to fabricate silicon-based optical modulators, which are in turn dependent on the electrical device structure implemented.

In general, both *p-i-n* diode [5-6] and transistor [4, 7-8] are two of electrical structures which have being frequently adopted for the designs of silicon modulators. In fact, the highest modulation depth achieved from our previously reported optical intensity modulators fabricated on silicon substrates [6] was ~4.15%. A low modulation depth obtained earlier could possibly be attributed to input coupling loss, free-carrier absorption loss, competing thermal-optic effect as result of inefficient heat dissipation, and others. In order to improve the modulation capability of said optical modulators, a three-terminal transistor structure similar to the work reported earlier by Sciuto *et al.* [7-8] was adopted for our study, except with the following differences. First, both *p*- and *n*-junction were created using a cost-effective spin-on-dopant (SOD) technique. We believe using a SOD method successfully bypasses a need of relying on a cumbersome ion implantation procedure to create *pn* junctions. Second, two additional trenches were defined and patterned on each side id Si rib waveguide via inductively-coupled plasma (ICP) dry etch method. The implementation of these two trenches would expect to bring better electromagnetic wave confinement and possible dissipation of heat as generated during the device operation. Finally, the source, drain, and gate regions of a transistor-based modulator were all patterned on the front side of the silicon wafer. We believe this device configuration would simplify the overall design and fabrication processes in the future if these modulators were purposely to be integrated with other photonic devices, which eventually leads to the so-called photonics integrated circuits (PICs).

This work describes the fabrication and characterization of a single mode optical waveguide modulator with the three-terminal transistor modulation structure fabricated on the silicon substrate. The single mode waveguide condition is to be achieved based on a rib waveguide structure with a large cross-section [9-10] and the pertinent waveguide dimensions (rib width/height and the neighboring slab waveguide thickness) are to be decided based on the simulation results of Beam Propagation Method (BPM).

EXPERIMENTS

A schematic diagram of the optical modulator with a three-terminal transistor waveguide structure is depicted in Fig. 1. The modulators were fabricated on a 7.5-μm-thick *n*-type Si epilayer (~2×10^{15} cm^{-3}) epitaxially grown on a heavily *n*-doped substrate (~2×19^{15} cm^{-3}). The silicon rib waveguide was realized via the lithographically patterning and ICP dry etch. The width (W) of the rib waveguide

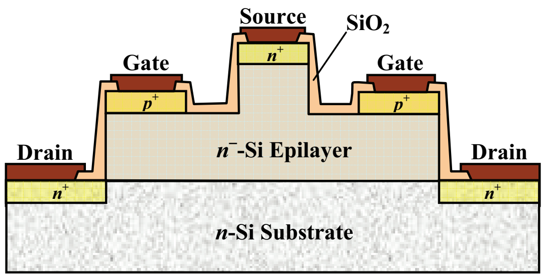

FIG. 1. A schematic diagram of a silicon modulator based on the three-terminal transistor waveguide structure.

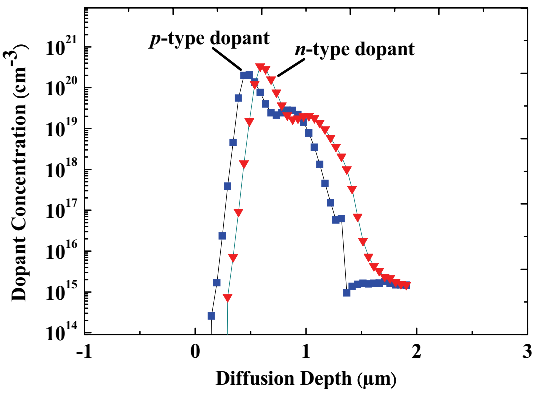

FIG. 2. The *p*- and *n*-type SOD dopant profiles determined using the spreading resistance probe (SRP) method.

varied from 9 μm to 13 μm with a 2 μm incremental step. For waveguide modulators with a particular rib waveguide width, there were nine different modulation lengths implemented; and they are, 100, 250, 500, 1000, 2000, 3000, 5000, 7000, and 9000 μm. The height of Si core is ~7.5 μm and the height of slab region on each side of the rib waveguide was kept around 6.5 μm. With these design parameters simulated using the BPM numerical method, the rib waveguide was expected to function as a single-mode waveguide. As mentioned earlier, the SOD method was adopted to form the heavily doped p^+ and n^+ regions with highest surface concentrations of ~2.09 × 10^{20} cm^{-3} and ~3.53 × 10^{20} cm^{-3}, respectively. The corresponding *p*- and *n*-type dopant profiles were determined using the spreading resistance probe (SRP) method, and the results are shown in Fig. 2. The diffusion depths of p^+ and n^+ regions were determined to be approximately ~1.3 and 1.6 μm, respectively. The 700-nm-thick SiO_2 was used as cladding and passivation layers. Finally, 300-nm-thick Al metallic contacts were deposited on the device. From an electrical point of view, the central n^+-type region acts as source, two n^+-doped regions in the *n*-type substrate function as drain, and the two lateral *p*-type regions then behave as gate. The separation between gate and source was designed to be 5 μm in order to prevent to the overlapping of these two regions from occurring. As already commented earlier, these two trenches were created for purposes of better optical waveguide confinement and helpful heat dissipation.

RESULTS AND DISCUSSION

Once the waveguide modulators were fabricated, the current-voltage (*I-V*) characteristics of these modulators were first measured using HP-4145 semiconductor parameter analyzer in order to verify electrically the existence of transistor structures being successfully achieved using the SOD method. The typical characteristics of drain current (I_D) versus drain-source voltage (V_{DS}) obtained for a modulator with the width of 11 μm and the modulation length of 2000 μm biased with different gate voltages (V_G) running from −8 V to −20V at an increment of −2 V are shown in Fig. 3. Generally speaking, this unique transistor structure thus fabricated was a joint version of junction field-effect transistor (JFET) and *p-i-n* diode, which relied on changing the electrical channel conductivity to subsequently modulate the optical signal propagating in the rib waveguide. Therefore, the resultant modulation index achieved is one of figures of merit measures the modulation capability of an optical waveguide

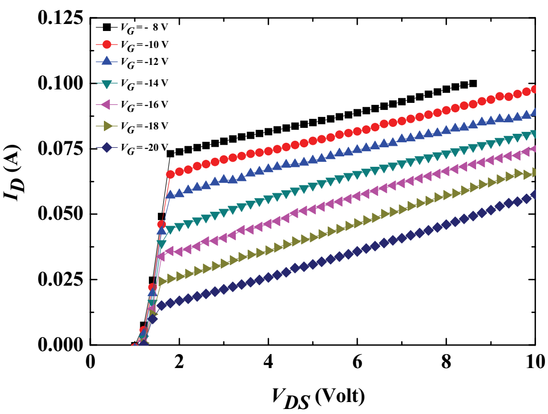

FIG. 3. The drain current (I_D) versus drain-source voltage (V_{DS}) characteristics obtained for a modulator with 11-μm-wide and 2000-μm-long biased with different gate voltages (V_G) running from −8 V to −20V at an increment of −2 V.

modulator. The operation of the modulator was demonstrated by employing 1.5 μm continuous-wave (cw) InGaAsP-based laser diode as a light source, and a germanium (Ge) photodiode as a detector. The laser beam was coupled into the waveguide modulator in normal direction, and both input and output ends of the modulator were polished in order to increase the coupling efficiency. The typical modulation depths gathered for modulators with the width of 7 μm and different modulation lengths spanning from 250 to 9000 μm biased at a gate current of 5 mA are depicted in Fig. 4. Notice that the resultant values

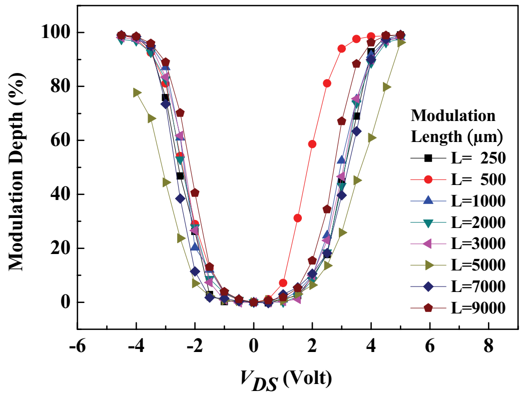

FIG. 4. The resultant modulation depths of modulators biased at a constant gate current of 5 mA. The dimensions of the modulators involved in this study all have the width of 7 μm but with different modulation lengths spanning from 250 to 9000 μm.

of modulation depth demonstrates virtually little or no dependence on the modulation length. In addition, a modulation depth close to 100% was achieved at a $V_{DS} \geq \pm 5$ V when a constant 5 mA gate current was applied.

CONCLUSIONS

In summary, we have successfully demonstrated a working silicon three-terminal transistor-based waveguide modulator, with a modulation depth close to 100% at $V_{DS} \geq$ 5 V when a 5 mA gate current is applied. The detailed device fabrication steps and the corresponding measurement results will be reported during the upcoming SSDM 2007 conference.

REFERENCES

[1] R. A. Soref, J. Schmidtchen, and K. Petermann, “Large single-mode rib waveguides in GeSi-Si and Si-on-SiO_2,” *IEEE J. Quantum Electron.*, vol. 27, pp. 1971-1974, 1991.

[2] A. Splett, T. Zinke, K. Petermann, E. Kasper, H. Kibbel, H. J. Herzog, and H. Presting, “Integration of waveguide and photodetectors in SiGe for 1.3 μm operation,” *IEEE Photonics Technol. Lett.*, vol. 6, pp. 59-61, 1994.

[3] M. A. Green, J. Zhao, A. Wang, P. J. Reece, and M. Gal, “Efficient silicon light-emitting diodes,” *Nature*, vol. 412, pp. 805-808, 2001.

[4] R. D. Lareau, L. Friedman, and R. A. Soref, “Waveguided electro-optical intensity modulation in a $Si/Ge_xSi_{1-x}/Si$ heterojunction bipolar transistor,” *Electron. Lett.*, vol. 26, pp. 1653-1655, 1990.

[5] C. K. Tang and G. T. Reed, “Highly efficient optical phase modulator in SOI waveguides,” *Electron. Lett.*, vol. 31, no. 6, pp. 451-452, 1995.

[6] R. W. Chuang and M.-T. Hsu, “Silicon optical modulators in silicon-on-insulator substrate based on the *p-i-n* waveguide structure,” *Jpn J. Appl. Phys.*, vol. 46, no. 4B, pp. 2445-2449, 2007.

[7] A. Sciuto, S. Libertino, A. Alessandria, S. Coffa, and G. Coppola, “Design, Fabrication, and Testing of an Integrated Si-Based Light Modulator,” *J. Lightwave Technol.*, vol. 21, no. 1, pp. 228-235, 2003.

[8] A. Sciuto, S. Libertino, S. Coffa, and G. Coppola, “Miniaturizable Si-based electro-optical modulator working at 1.5 μm,” *Appl. Phys. Lett.*, vol. 86, pp. 201115/1-201115/3, 2005.

[9] R. A. Soref, J. Schmidtchen, K. Petermann,“Large Single-Mode Rib Waveguides in GeSi-Si and Si-on-SiO_2,” *J. Quantum Electronics*, vol. 27, no. 8, pp. 1971-1974, 1991.

[10] S. Pogossian, L. Vescan, and A. Vonsovici, “The Single Mode Condition for Semiconductor Rib Waveguides with Large Cross Section,” *J. Lightwave Technol.*, vol. 16, no. 10, pp. 1851-1853, 1998.