論文の内容の要旨

Thesis Summary

論文題目

Study on optical modulator and switch based on the III-V/Si hybrid MOS optical phase shifter

(III-V/Si ハイブリッド MOS 光位相シフタに基づく光変調器および光スイッチに関する研究)

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With the continuous huge research effort and investment by academic institutes and industry respectively, Si photonics has rapidly grown into a mature and established platform promising large bandwidth, low cost and high-level integration with the traditional electronic devices, by leveraging the complementary metal-oxide-semiconductor (CMOS) manufacturing facilities. In optical communication and networking systems, optical modulator and switch are two critical building blocks for both of which an optical phase shifter is an indispensable component. On Si photonics platform, most optical phase shifters are either based on the thermo-optic effect or carrier dispersion effect, which suffer from large power consumption, low modulation efficiency, or severe absorption loss. To address these challenges, a III-V/Si hybrid MOS optical phase shifter is proposed and demonstrated. The III-V/Si hybrid MOS optical phase shifter was formed by bonding a n-type III-V layer on a p-type Si waveguide using a high-k dielectric layer as the bonding interface. With a positive gate voltage applied between the Si and III-V layer, holes and electrons are accumulated on the MOS interface, modifying the local refractive index and changing the phase of the optical mode. Owning to the small effective mass of electrons in the III-V material, the free-carrier plasma dispersion effect is enhanced leading to higher modulation efficiency. Furthermore, the high electron mobility enables smaller resistance resulting into larger modulation bandwidth. The III-V/Si hybrid MOS optical modulator has demonstrated a low $V_{\pi}L$ of 0.047 Vcm and low absorption loss of 0.23 dB at π phase shift. Compared with its Si counterparts, the modulation efficiency was increased by 5 times while the absorption loss was reduced by 10 times.

Although the III-V/Si hybrid MOS optical phase shifter has exhibited excellent performance, there is still plenty of room for improvement. In this dissertation, we have improved the III-V/Si hybrid MOS optical phase shifter in terms of modulation efficiency and modulation bandwidth, integrated it on a Si 2×2 optical switch and a Si racetrack resonator, and proposed a new

modulation scheme to break the inherent trade-off relationship between modulation efficiency and modulation bandwidth.

Firstly, the performance dependence on the structure of III-V/Si hybrid MOS optical phase shifter was numerically studied systematically. The influence of doping concentration and layer thickness of III-V and Si layers, and equivalent oxide thickness (EOT) of the oxide layer inserted between III-V and Si layers was analyzed. It was found that the modulation efficiency was able to be increased by improving the overlap between optical mode and accumulated free carriers on the MOS interfaces. EOT scaling is effective to increase the modulation efficiency. However, when Al_2O_3 is used as the bonding interface, the EOT is difficult to be scaled below 5 nm due to the generation of nano-scale voids in the bonding interface. By employing HfO_2/Al_2O_3 stack for wafer bonding, an EOT as small as 3.5 nm was successfully achieved, which is expected to produce a low $V_{\pi}L$ of 0.035 Vcm. The modulation bandwidth was increased by removing the parasitic capacitance. After introducing an isolation trench on the one side of the Si slab waveguide, 86% parasitic capacitance was successfully eliminated. To fully eliminate all the parasitic effect, a SiO_2 filling process followed by a chemical mechanical planarization (CMP) process was proposed. Preliminary wafer bonding test was conducted and verified the feasibility of the proposed methods.

In addition, a 2×2 Si Mach-Zehnder interferometer (MZI) optical switch based on III-V/Si hybrid MOS optical phase shifter was demonstrated. Owing to the negligible gate leakage current in the hybrid MOS capacitor, the power consumption required for switching is 0.18 nW, approximately one million times smaller than that of a Si thermo-optic phase shifter. A switching time of less than 20 ns was also achieved, which is 1000 times faster than a Si thermo-optic phase shifter. A 4×4 optical switch is now under development, which is a prototype for large scale optical switch fabrics or photonics circuit used for deep learning applications. Next, the III-V/Si hybrid MOS optical phase shifter was successfully integrated on a Si racetrack resonator. The Si racetrack resonator was well designed to achieve the critical coupling condition that lowers the driving voltage swing or capacitance for optical intensity modulation. Compared with a MZI optical modulator with the same phase shifter, the demonstrated racetrack resonator only need halved driving voltage and one quarter energy for 10-dB optical modulation.

For all the MOS-type optical modulators based on carrier accumulation, the trade-off relationship between modulation efficiency and modulation bandwidth is a challenging issue. To break this limitation, an efficient optical modulator by reverse-biased III-V/Si hybrid MOS capacitor was proposed and demonstrated. It was found that, by carefully engineering the wavelength detuning and doping concentration of III-V and Si layers, a high modulation efficiency could be achieved by combing the Franz-Keldysh effect and carrier depletion.

Moreover, the small capacitance under the depletion mode enhanced the relationship between modulation bandwidth and energy per bit. A III-V/Si hybrid MOS optical modulator working under reverse bias has been experimentally demonstrated with a low $V_{\pi}L$ of 0.12 Vcm. Compared with forward biased case, the reverse biased optical modulator required halved capacitance, which improved modulation bandwidth and energy consumption, simultaneously.

In summary, the III-V/Si hybrid MOS optical phase shifter has been improved and successfully applied on the optical modulator and optical switch, which are very attractive for high-speed data communication and large-scale optical networking.