Si Nano-Photonics Innovate Next Generation Network Systems and LSI Technologies

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Abstract

"Si nanophotonics" controls light by employing a nano-scale structural technology. Featuring state-of-the-art technologies to manufacture LSI chips, Si nanophotonics technology enables impressive miniaturization and achieves low power consumption compared to the conventional optical elements technologies. Optical signal transmission of the LSI chip has not hitherto been realized, however by adopting this Si nanophotonics technology to the elements of an LSI, NEC demonstrated the possibility to significantly improve LSI performance. With this technology NEC is proposing to create new devices to support next generation networks and LSI innovations.

Keywords

silicon, photonics, post-NGN, LSI optical wiring, optical switch, optical functional element, plasmon, nano-photodiode

1. Introduction

The advanced information society of today is supported by two major technology domains. These are IT (Information Technology) and NW (network) technologies. **Fig. 1** describes the main functions, devices, technologies, features and outlines of issues of these two technology domains.

The key device of the IT technology domain is the LSI (Large-Scale Integration) chip, which employs Si (silicon) as its material. By providing nano-scale processing to Si materials, which shows superior performance as semiconductor materials, LSI has improved its performance of functions as well as its mass production methods. However, the performance of LSI internal signal transmission is recently facing its limit in speed and distance, which may present a barrier to further improvements in system performance.

In the NW technology domain that is required to transmit signals over long distances communications using optical fiber are main stream. The advantageous features of optical fiber communications are reduced transmission loss, higher speeds and long distance transmission because it can transmit various different wavelength signals at the same time via a single fiber. The key devices of this domain are the optical transceiver, which dispatches and receives signals and the optical switch that switches over the signal path. However, it is difficult to reduce the size and cost of these key devices as much as those of the LSIs.

These two technology domains have to adapt their respective strategies to support each other. This paper introduces Si pho-

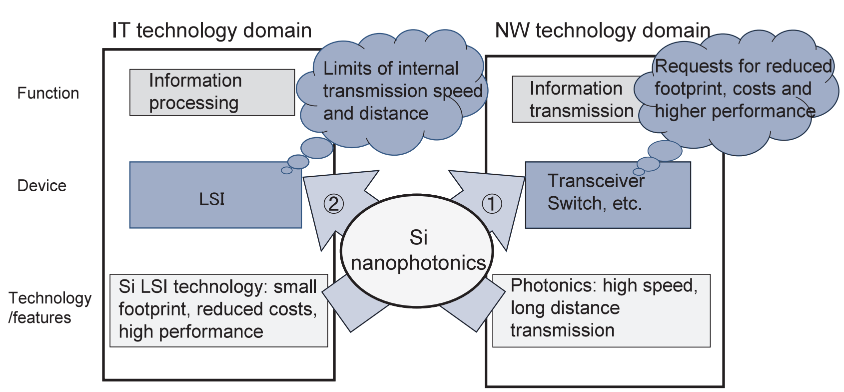

Fig. 1 Features and problems of IT and NW technologies.

tonics, which is a new technology for solving several problems that exist in both domains by fusing the Si LSI processing technology and optical data transmission technologies. NEC is developing two main technologies using Si photonics; 1) reducing footprint size, cost down and high performance for network devices by adopting LSI processing mass production technology, 2) overcoming limit of transmission speed and distance by adopting optical transmission for the internal signal transmission inside a LSI, an electronics device. This paper introduces these two technologies.

2. Miniaturizing and Achieving High Performances for Optical Communication Devices Employing Si Nano-Photonics

A broadband access network that enables the transmission of large volumes of data, such as high-quality video data via the Internet is being widely adopted. In support of this environment, increasing data volume and improving transmission efficiency in metro areas and for backbone networks that bind various access points of the networks is required. Moreover, miniaturization needs, cost reduction and low-power consumption of telecommunications optical devices that are installed in homes, offices, telephone centers, etc. have been increasing.

An LSI substrate material, Si has the following features as an optical material encourages the interest of engineers in optimizing these features.

- Transparent near-infrared wavelength to be used for optical fiber communications
- High refractive index, which is suitable for reducing the size of optical devices
- High variation in heat refractive indices that are suitable for reducing the size and power consumption of a device
- Applicable to conventional LSI manufacturing units for enabling mass production and reducing costs
- Capability of integrating electronic IC and an opto-electronic IC, thus enabling achievement of high performances

Supported by the above physical features of Si and by applications of the LSI fine processing manufacturing technologies it is expected to advance miniaturization and to integrate optical functional elements in order to mount network units on modules or single chips.

In this paper, a waveguide micro optical switch is introduced as an example. The optical switch is an essential optical functional device for the efficient operation of optical networks and it switches the optical signal path without converting optical signals into electrical signals. In order to switch over multiple optical signal paths at the same time it is necessary to integrate multiple switching elements, therefore each element has to be miniaturized. NEC has developed a prototype of the world-smallest 1×4 optical switch and has succeeded in demonstrating its operation.[1)]

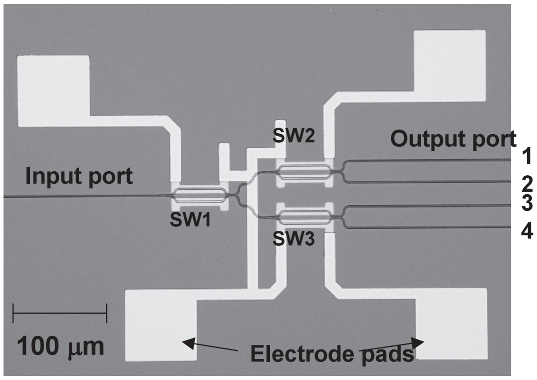

Fig. 2 Micrograph of 1×4 optical switch chip.

A micrograph of the prototype 1×4 optical switch chip is shown in **Fig. 2**. NEC's 1×4 optical switch is composed of three Mach-Zehnder interferometer type switching elements. A heater is mounted on one arm of each interferometer. The optical waveguide is heated and varies the refractive index causing the optical interference to vary and switch the optical path. Because the refractive index of Si varies greatly according to the heat, the length of each switching element can be reduced to a size of approximately 40μm. As described above, Si has a characteristically high refractive index. This characteristic is efficient in confining optical signals to the waveguide so that the waveguide can be bent to a smaller radius and the distance connecting each element can thus be reduced. This results in greatly reducing the overall size of the 1×4 switch which is composed of three switching elements by up to 200 × 120μm.

Fig. 3 shows the operational test results of the 1 × 4 optical switch prototype. The white dots indicated by arrows at the input and output ports are the locations of the input and output optical signals. By switching two of the three switching elements ON/OFF, optical signals can be output to all of the four output ports.

The manufacturing process of this optical switch is rather simple. The process is 1) forming the core of the optical waveguide by etching part of Si surface layer of the SOI (Silicon on Insulator) substrate, 2) embedding the core by forming a silicon dioxide film and 3) forming heating points and electrodes by forming films of resistive elements and etching conductive paths onto a silicon dioxide film.

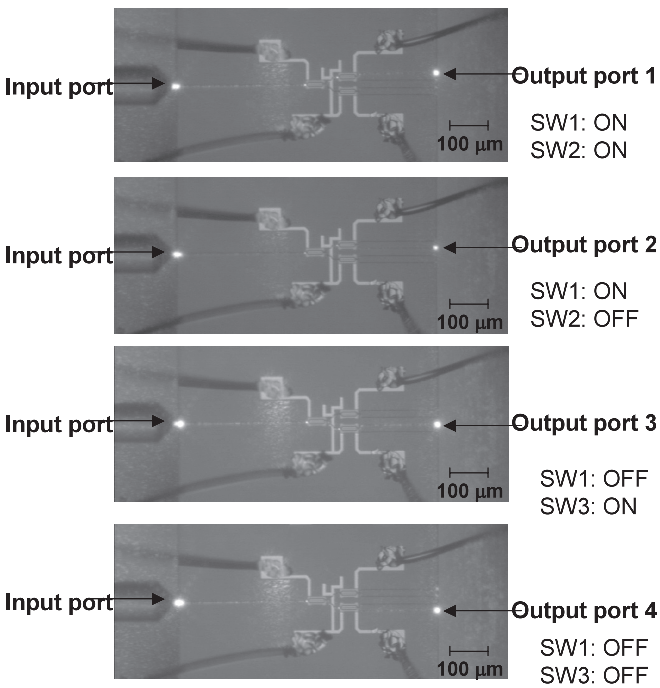

Fig. 3 Operational test of the 1×4 optical switch.

3. Si Nanophotonics Technology for LSI Optical Wiring

As a technology that provides an even greater impact to the industry, NEC is examining an optical wiring technique that is expected to transcend the performance limits for LSI electrical wiring. In several years, even within a scale of centimeters, that is comparable to an LSI chip size, the speed, noise and wiring space of electrical wiring systems will be issues that need to be solved. The development of an ultra-small optical modulator, a photodetector, an optical waveguide or a wavelength multiplexing/demultiplexing element by employing the Si nanophotonics technology is expected to solve these issues by installing them on an LSI chip together with the electronic circuits.

To install the optical wiring on an LSI, it is necessary to reduce the size and power consumption of the optical modulator that converts the electrical signals of the electronics element into optical signals and also those of the photodetector that converts the optical signals into electrical signals. By integrating and fabricating these optical elements on the LSI, it becomes possible to form optical wiring structures on it.

The development of nano-photodiode[2], a new compact light receiving element, is one of the developments that has made significant progress in miniaturizing and reducing the power consumption by applying the Si photonics technology. NEC has succeeded in forming a structure called a surface plasmon antenna. As a result of the effects of this antenna, a photodiode of very high speed and high sensitivity is realized with a low-cost Si process.

The nano-photodiode is a device that employs a technology to use near-field light collected by the surface plasmon antenna. The surface plasmon antenna collects incident light to a single point by a metal thin film incorporating cyclic grooves (several concentric circles are applied to the prototype) as shown in **Fig. 4(a)**. This structure is formed with pores smaller than the wavelength size (approx. 200nm dia.) located at the center of the metal film by a processing engineering technique that employs nanotechnology. Also, additional processing is applied around the pore peripheries. A light is entered to these pores and a surface plasmon, which is a resonant wave of free electrons, is formed as shown in **Fig. 4(b)**. This surface plasmon formation enables the generation of strong near-field light around the pores on the rear side of the metal film.[3] Near-field light can be localized to a point smaller than the wavelength. High-speed and high-efficiency characteristics can co-exist by detecting the near-field light by the semiconductors.

Fig. 5 shows an illustration of a Si nano-photodiode structure including Si mesa. The near-field light generated around the

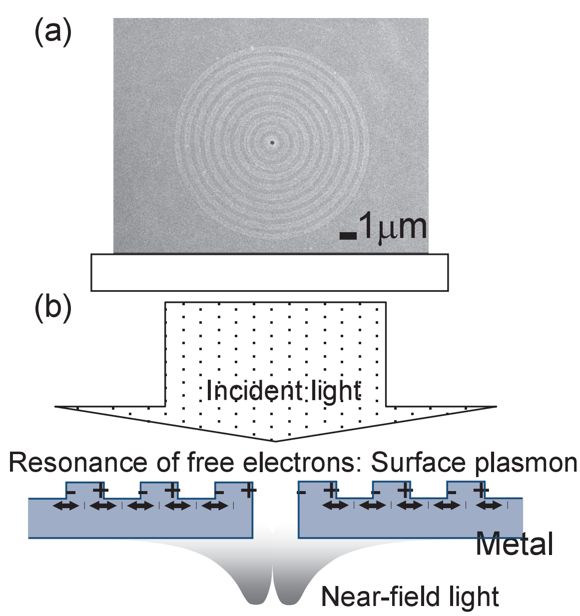

Fig. 4 (a) Scanning electron micrograph of the plasmon antenna, (b) Cross section of the plasmon antenna and resonance phenomena of the incident light and surface Plasmon.

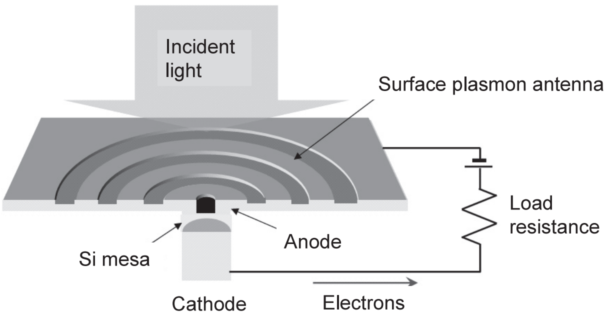

Fig. 5 Illustration of a Si nano-photodiode.

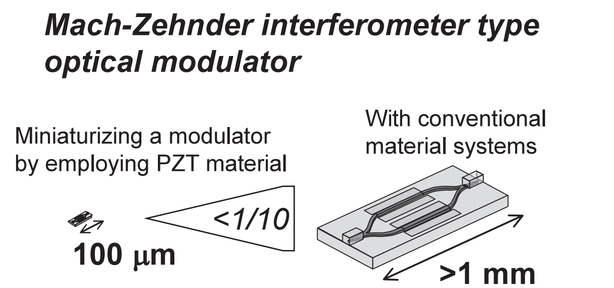

Fig. 6 Possibility of miniaturizing the optical modulator by employing PZT material.

pores located at the center of the surface plasmon antenna is absorbed by a micro-fine semiconductor, the Si mesa structure. A comparison test, with and without the plasmon antenna, shows an increase of generated current efficiency by the order of dozens of times.[4] With regard to the response time, a current output of approximately 20ps plus is confirmed for a response to the optical short pulse, and a response capability for high-speed optical signals of around 50GHz is expected.

NEC is planning to apply this nano-photodiode technology to high-speed optical communications and the high-sensitivity photodetector. It is also critically examining its use as a photodetector for optical wires on LSIs. For example, it is suggested to design a optical clock distribution system that carries out global clock by light signals in a LSI.

To carry out data communications between chip cores, LSIs marketed in the multi-core generation are expected to incorporate technologies to send optical signals as well as to receive optical signals. An optical modulator converts electrical signals into optical signals. NEC is proposing the development of an optical modulator with a micro size structure and low operation-voltage by employing a ferroelectric ceramic composed of nano scale (smaller than 20nm) crystal particles. Piezoelectric material (PZT: Pb (Zr, Ti) O_3) is formed by an aerosol deposition method and applies it to an interference-type optical modulator. According to the basic material characterizations, the EO coefficient that indicates the refractive index change according with the electrical field change has become 150pm/V, which is one order larger than that of the conventional materials.[5] This result indicates the possibility of reducing modulator size to that can be mounted on an LSI chip after a realistic device is designed. **Fig. 6** indicates our proposed miniaturization of a Mach-Zehnder interferometer type optical modulator employing PZT material.

As explained above, this paper has introduced a technique for converting electrical signals into optical signals by employing Si nanophotonics for the optical wiring of LSI chips.

4. Conclusion

With the evolution of Si nanophotonics, the miniaturization of optical elements is becoming capable of mounting them on LSIs or on compact, high performance optical modules for optical networks. Si nanophotonics is expected as an innovative technology to be employed for high-speed and large-volume telecommunications technologies and LSIs for computer elementary elements.

This paper has introduced technologies able to attain high performance optical networks and LSI optical wiring by employing Si nanophotonics. With regard to the advanced society of the future, by developing a wavelength multiplexing optical network on an LSI chip, the functionality of an LSI is expected to be greatly improved. However, in order to materialize such technologies, it is necessary to develop an ultra-small wavelength control element. NEC is proposing to develop new optical functional technologies by controlling light characteristics at the nano-scale.

References

1) T. Chu et al.; “Compact 1 × N thermo-optic switches based on silicon photonic wire waveguides,” Optics Express, Vol.13, No.25, p10109, 2005.
2) Ohashi, et al.; “PURAZUMON KYOMEI WO MOCHIITA KINSETSUBA HIKARI ZOUKYO Si NANOFOTODAIODO” (Silicon nano-photodiode using optical near-field enhanced by surface-plasmon resonance), OYO BUTSURI, Vol. 74, p.1453, 2005.
3) Ebbesen, T. W. et al.; “Extraordinary optical transmission through subwavelength hole arrays,” Nature 391, 667 (1998).
4) Ishi, T. et al.; “Si Nano-Photodiode with a Surface Plasmon Antenna,” Jpn. J. Appl. Phys. 44, L364 (2005).
5) Fujikata, J. et al.; “Highly enhanced speed and efficiency of Si Nano-Photodiode with a Sur-face-Plasmon Antenna,” Proc. Int. Conf. Solid State Devices and Materials, Kobe, E-3-3, 2005.
6) Nakada, M. et al.; “Electro-Optic Properties of $Pb(Zr_{1-x}Ti_x)O_3$ (X=0, 0.3, 0.6) Films Prepared by Aerosol Deposition,” Jpn. J. Appl. Phys. 44, L1088 (2005).

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