Membrane Photonic Integration on Si Platform

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***Abstract*— Toward the practical use of on-chip optical interconnection in Si LSIs, we have set an 'InP-based membrane photonic integrated circuit ' on a Si substrate using adhesive bonding and demonstrated low-energy digital transmission in the membrane.**

I. Expecting On-Chip Optical Interconnection in LSIs

The progress of Si LSIs is a history of technological innovations being led by the concept of 'scaling.' According to Moore's law, the semiconductor technology roadmap was first produced by SIA in 1993 and is continued as ITRS since 1998. Directed by the roadmap, persistent efforts have been made to downscale design rules, and recently the 14-nm-node technology has reached in shipping devices [1]. Moreover, the 10-nm technology is going to succeed the 14 nm, and ITRS predicts that 4.5nm-gate MOSFETs and 1-terabit memory chips will come into practical use by 2022. Riding on this wave, Si LSIs have rapidly increased the degree of their integration and incorporated all components needed for computers and other applications (e.g. SoC). This has greatly raised the processing capability and reduced the total power dissipation of electronic systems. At the same time, however, *RC* time delay in metal interconnection has become a dominant limiting factor on system performance, which is known as an 'interconnect bottleneck.'

To overcome the bottleneck, two sophisticated methods were proposed and demonstrated to replace long metallic interconnects. One is an electrical method that divides a large chip into stacked many dies and interconnects them vertically by using through-silicon vias [2] or inductive-coupling data transmission [3]. The other method is to use on-chip optical interconnection instead of metallic ones. Unlike electrical counterparts, optical interconnection is negligible from transmission delay and electromagnetic interference; besides, it is compatible with multiplexing large-capacity data transmission. Therefore, optical interconnection is superior to electrical ones if it can be easily combined with Si LSIs [4]. To have an advantage over existing interconnections, it is indispensable to monolithically integrate an optical data-transmission circuit consisting of lasers, transmission lines, and photodetectors on a substrate, and operate them with a transmission speed of more than 10 Gbps and an energy dissipation of less than 100 fJ/bit [5].

To put optical interconnection into practical use, we proposed a method of hybrid optical-electrical interconnection that uses InP-based membrane photonic integrated circuits. Figure 1 shows the concept. The InP-based membrane (O9) with optical data-transmission circuits is attached on a Si LSI chip with multilevel interconnection (M1-M8), using adhesive bonding. That is, the uppermost interconnection (O9) of the LSI is optical and not electrical. This enables to realize high-speed data transmission between distant circuit blocks in the Si LSI. The lasers and detectors in the data-transmission circuits are connected to driving and amplifying circuits on the Si LSI, using through-silicon vias. The details are described in the following.

II. Components Used in Membrane Optical Transmission Circuits

Most optical devices used in photonic integrated circuits have the form of an InP-based planar waveguide. The point

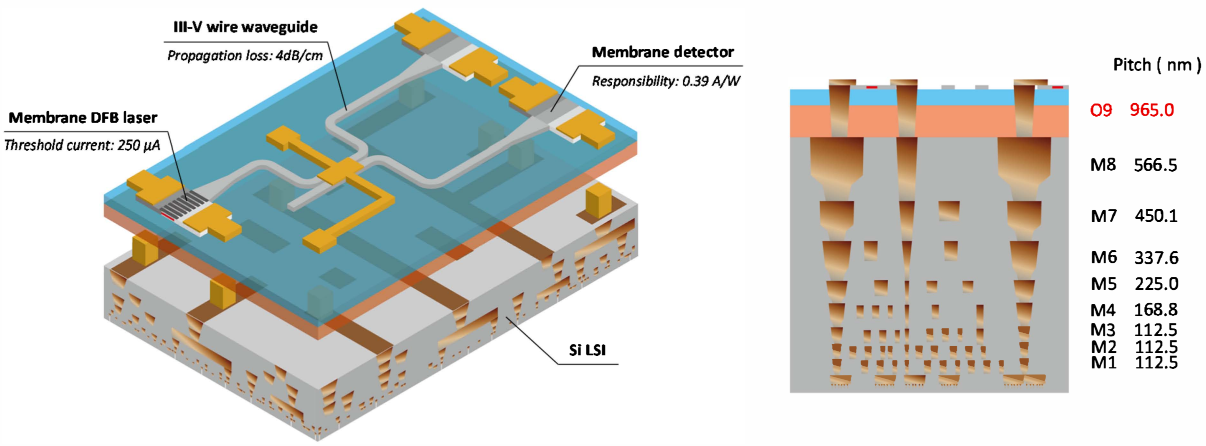

Fig. 1. Hybrid optical-electrical interconnection using InP-based membrane photonic integrated circuit as interconnection of LSI.

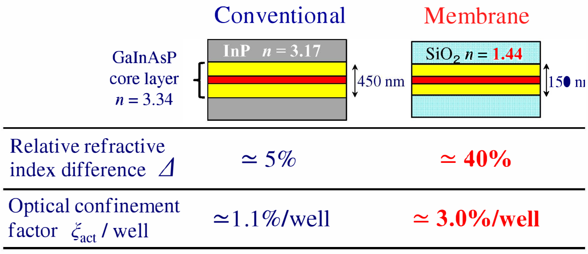

Fig. 2. Membrane structure as compared with ordinary one.

of our idea is to make the core of waveguides in a form of a membrane (thin film) sandwiched between two SiO_2 layers (upper layer can be air) (see Fig. 2) [6, 7]. We use a GaInAsP membrane for the core. Strong optical confinement in the core can be obtained because the refractive index of SiO_2 is far smaller than that of GaInAsP. This is quite favorable for optical devices as below.

A. Membrane laser

A laser made in a membrane can achieve strong optical confinement in its gain region, thereby operating at very low power as compared with ordinary semiconductor lasers. The device we made is driven with lateral current injection because there is insulating polymer beneath the membrane. We have confirmed a low threshold current of 230 μA, an external differential quantum efficiency of 5%, and capability of 100-fJ/bit operation [8].

B. Membrane photodetector

Strong optical confinement in the light detecting region enables to reduce the area, therefore capacitance, of the detecting region. This is favorable for high speed operation because the speed of the receiver is limited only by the small input capacitance of a preamplifier [9]. The membrane detector is suitable for on-chip optical interconnection, which needs both high-speed and low-power operations. We have made the device with a lateral-current structure and confirmed a light sensitivity of 0.39 A/W and a dark current of 5 nA [10].

C. Membrane waveguide

Low-loss waveguides for high density interconnection can be achieved because of the strong optical confinement in the GaInAsP core. We have confirmed a transmission loss of 4 dB/cm [11], which is comparable with Si wire waveguides.

III. MEMBRANE INTEGRATION TECHNOLOGY

Figure 3 shows the photomicrograph of the optical circuit. We used a DFB laser with a 30-μm long resonator and a 200-μm long PIN photodiode, and connected them using a 500-μm long waveguide. The cross section of the connection part is shown in Fig. 4, where the butt-jointed built-in (BJB) technology is used (see [12] for details). In the DFB laser, a λ/4-phase-shift region was inserted in the center of the resonator to reduce resonator length and stabilize oscillation modes. In this device, both the laser and the photodiode had the same structure of strain compensated five-quantum-wells.

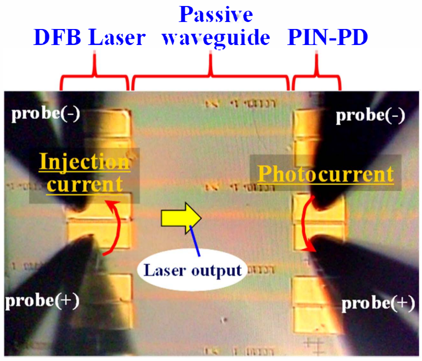

Fig. 3. Photomicrograph of GaInAsP/InP membrane photonic integrated circuit attached on Si substrate.

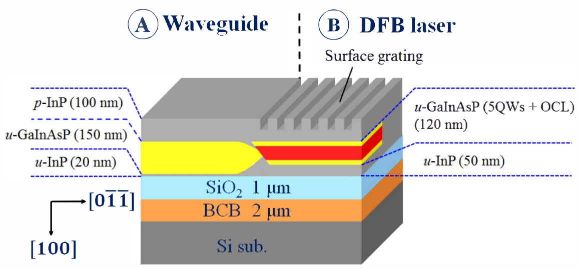

Fig. 4 Connection between laser and waveguide in GaInAsP membrane.

The GaInAsP membrane was attached on a Si substrate, using benzocyclobutene (BCB) based polymer. A photo current of 3 μA was obtained for the laser driving current of 0.5 mA (backward output was 3 μW). Our circuit is capable of 100 fJ/s operation and expected to contribute to solve the interconnect bottleneck in LSIs.

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