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On-chip Optical Interconnects using InGaN Light-Emitting Diodes Integrated with Si-CMOS

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Abstract: We propose and design on-chip optical interconnects using InGaN light-emitting diode light source within an integrated process platform with Si-CMOS circuits. The device and system design, simulation, processing, and preliminary results are presented.

The rapid development of multi-core processors places increasing demand for on-chip communication bandwidth and power-efficiency. The fundamental limitations of electrical interconnects for handling the demands of growing core counts have been recognized and the scaling of CMOS technology does not solve this problem due to the increasing power-consumption with link distance and bandwidth. Recently, optical interconnects have been widely studied and it was suggested that they have larger communication bandwidth and potentially better power efficiency than electrical interconnects [1]. There are a number of efforts in exploring the viability of photonic Network-on-chip (NoC) that use lasers as light sources and microring resonators as modulators and routers. The versatility of these resonant devices enables various innovative designs of NoC architecture by leveraging multiple wavelengths with associated switches and filters [2]. However, the laser sources lead to substantial power consumption, partially because continuous light output is usually necessary in order to enable external modulation to obtain high modulation bandwidth and extinction ratio. Prior studies have therefore concluded that it is challenging for laser-enabled optical interconnects to replace electrical interconnects as the on-chip communication fabric for the highly dynamic traffic patterns of many-core processors [1].

We propose an optical interconnection method that uses directly-modulated light-emitting diodes (LEDs) made by InGaN/GaN materials grown on silicon substrates. Unlike designs using lasers, links based on incoherent light sources such as LEDs can only function with NoC architectures that can multiplex traffic flows atop 1-to-1 connections, i.e., where control and switching needs to be done with electrical routers. Optical routers based on resonance such as microrings are not applicable for filtering, modulating and switching, and wavelength-division multiplexing (WDM) cannot be used to enable 1-to-many or many-to-many connections. In short, the LED enabled interconnection is best used for point-to-point interconnects targeting low power consumption. The advantage of using InGaN/GaN is that the epitaxy technology of III-Nitrides on (111) silicon is more practical than other III-V semiconductors epitaxy on Si substrates. Applications of III-Nitrides in solid-state lighting have been widely used and commercialized. In contrast, the reliability and quality of other III-V optoelectronic devices, when directly epitaxially grown on Si substrate, do still not meet the requirements for practical applications. In our proposed method the optical devices and link will be fabricated on Si (111) substrate before any electrical components. CMOS processing and components will be integrated on the

processed optical link wafer via wafer bonding technology and back-of-end-line processing [3,4]. System simulation, evaluation, and preliminary measurement results of InGaN multiple-quantum-well (MQW) LEDs and photodetectors indicate low power-consumption and very promising application of this technology as on-chip optical interconnects for many-core processors.

Figure 1 shows the integration scheme of the InGaN LED optical link and CMOS circuits. AlN/AlGaIn buffer layers are grown on (111) Si substrate and followed by intrinsic GaN and n-GaN layer. InGaN/GaN MQW layers are then grown on the n-GaN layer and capped by a p-GaN layer. The LEDs consist of the MQW layers with n- and p-GaN contact layers. Photodetection can be realized either by the same MQW layers or by an additional InGaN layer atop of the LED layer. Silicon nitride layers for waveguiding between LEDs and photodetectors are then etched and filled by SiO_2 and SiN_x dielectric layers. Planarization is necessary to form low-loss waveguides. At the target wavelength of 450nm, SiN_x is transparent and a transmission loss of lower than 1dB/cm was demonstrated before. The short operation wavelength of ~450nm and relatively high refractive index contrast between SiO_2 and SiN_x makes a single-mode waveguide very compact. Our simulation indicates that a waveguide cross section of $\sim 300\text{nm} \times 180\text{nm}$ can support single TE mode with a confinement factor of larger than 80%. The same single-mode waveguide can also be formed in the InGaN/GaN LED layer with an additional optical confinement layer. Therefore single-mode operation is possible in this optical link. After the processing of the photonic layer the entire wafer will be covered by a SiO_2 layer and then bonded to a Si (001) wafer in a double bonding process to add photonic drivers and CMOS devices. This is necessary because the epitaxy temperature of nitrides is typically above 1000°C , a temperature at which the CMOS circuits cannot survive. Metal vias will be opened in the dielectric layer during the CMOS back-end process to electrically connect electric and photonic layers.

Figure 1. Optical link system using InGaN/GaN LED and photodetectors. The Si (100) CMOS layer is bonded after photonic layer's processing.

A test wafer with epitaxial-grown GaN/InGaIn nitride layers is used to fabricate micro-LEDs with different sizes. We found that the turn-on voltages remain constant at $\sim 3.0\text{V}$ regardless of the very different sizes. This indicates the robustness of these LEDs. Smaller LEDs have better current-spreading and therefore under the same bias voltage they have higher current densities than bigger LEDs. Figure 2(a) shows current density-Voltage (J-V) curves of $2\mu\text{m}$ -wide micro-LEDs with different lengths. In a $20\mu\text{m}$ -long LED at 2.9V and $1\mu\text{A}$, blue light emission is visible to the eyes. Therefore very low power operation is possible in these micro-LEDs if they can be modulated up to 1GHz. All the LEDs Capacity-Voltage measurement results are below the instrument's detection limit of 10fF. This means that fast modulation of the LEDs will not be restricted by RC-delays. Therefore the bandwidth of these LEDs can be well above 1Gbit/s [5].

Figure 2(b) shows system evaluation results of an optical link using LEDs. We evaluate the energy efficiency of our LED-enabled link against a baseline electrical clockless repeated link in the 45 nm node and a

laser-enabled link using DSENT, a timing-driven NoC power modeling tool [1]. The laser-enabled optical link is composed of off-chip laser, microring modulator, receivers and peripheral electrical devices. We use electrical LED modeling and estimate the associated Si-driver size in DSENT. In particular, the effective capacitance of the LED (6.3 fF) and parasitic capacitance of the vias (1.7 fF) are used to size the driver and its power consumption. Waveguide loss is set to be 1 dB/cm and responsivity for the detector is set to be 0.1 A/W. These parameters were determined through detailed modeling of optical parameters using the PICWave module of Photon Design software. For short distances (<8mm), most power is consumed by the electrical circuits in the opto-electronic link. Therefore, it is shown in Figure 2(b) that the energy for the electronic links increases linearly while the energy for the optical links remains almost constant regardless of transmitting distance. The LED-enabled links outperform the other designs with a power efficiency of 38fJ/b.

Figure 2 (a) J-V curves of 2 μ m-wide LEDs with different length; (b) Comparison of energy efficiencies of electrical link, optical link using LED and laser.

In summary, a photonic link using InGaN/GaN LEDs targeting at low-power consumption is proposed. The system integration method, energy efficiency evaluation, and initial measurement results of the test devices are presented. Preliminary results indicate that using InGaN/GaN LEDs in an optical-link integrated with CMOS for low-power on-chip optical interconnects is feasible.

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