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On-chip optical interconnect on silicon by transfer printing

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Abstract: On-chip optical interconnects consisting of transfer-printed micro-LEDs and photodiodes are presented. Static and dynamic data transmission and bi-directional interconnect are demonstrated. The results show the potential for cost-effective and small form-factor on-chip opto-isolators.

OCIS codes: (200.4650) Optical interconnects; (250.5300) Photonic integrated circuits;

1. Introduction

Opto-isolators, mainly consisting of light emitting diodes (LEDs) and photodiodes (PDs), have been widely used for voltage isolation in electrical circuits for more than forty years. On-chip application of traditional opto-isolators has been limited due to cost and large form-factors. Recent progress in mass-transfer micro-assembly and microscale optoelectronic devices [1] provides the opportunity to develop a new class of on-chip opto-isolators with attractive cost structures and form-factors.

On-chip optical interconnects on Si have been demonstrated by the integration methods such as flip chip [2] and wafer bonding [3], but they are also limited by time-consuming integration or inefficient material utilization. Transfer printing is a promising technology for heterogeneous device integration and is being used in micro LED displays, and also with components such as laser diodes, photodetectors, photovoltaic cells and so on [1, 4]. In this paper, microscale LEDs and PDs are assembled onto silicon by transfer printing and the on-chip optical interconnect operating at 1.55 um is achieved using a polymer waveguide formed between the printed devices. A compact volume of less than $0.4\times0.2\times0.005$ mm^3, current transfer ratio (CTR) up to 1‰, low power consumption of 1 mW and data transmission speed of 1 Mbit/s are achieved. The optical coupling efficiency between the LED and PD is enhanced by 60 times using a polymer waveguide. These results demonstrate that the combination of advanced assembly and microscale high performance light emitters and detectors will lead to cost-effective miniaturized on-chip optical interconnects.

2. Design and fabrication

The interconnect consists of an LED, PD and polymer waveguide built between them, as shown in Fig. 1. A wavelength of 1.55 μm is selected to avoid any absorption in silicon circuits. The LED and PD are fabricated on an epitaxial wafer with 6 AlGaInAs quantum wells. An AlInAs sacrificial layer [5] is grown on top of InP substrate to permit the undercutting of the LEDs and PDs from the substrate. Square structures with widths of 10 μm, 20 μm and 50 μm are used for the LEDs. The backside and two sidewalls of each LED is coated by a dielectric film and metal layers to reflect light towards the front facet. Polymer waveguides are fabricated with the photoimagable epoxy SU-8 2000 because of its high dielectric strength ($>10^6$ V/cm) needed for electrical isolation, and they have a length of 100 μm and widths of 10 μm larger than those of the LEDs they connect with. The PDs are rectangular with a length of 100 μm and widths of 10 μm larger than those of SU-8 waveguides they connect with.

For this demonstration an epitaxial wafer for the LEDs and PDs is grown on a common InP substrate. The device epitaxy consists of the sacrificial layer, n-type cladding layer, active region, p-type cladding layer and contact layer. In the device process, the sample is firstly deposited with p-type metals for LEDs and PDs, and then mesas are fabricated by etching into n-type cladding layer. Then n-type metals are deposited and defined on top of the etched area, and dielectric film of SiO_2 is coated on the surface and sidewalls with windows opened on top of p-type and n-type metals. Thick metal pads and alignment marks for transfer printing are defined on device surface. After that, LEDs and PDs are fabricated by etching through n-type cladding layer to the top of sacrificial layer. Grating features [6] are patterned in sacrificial layer and the devices are coated with a protective resist. The sacrificial layer is then undercut in the $FeCl_3$ solution and the LEDs and PDs are picked up by an elastomer stamp and printed to an adhesive-coated Si wafer with a printing accuracy better than ±2 μm. The adhesive layer is thermally cured to strengthen the adhesion between printed devices and Si wafer. Finally, an interconnect path is built by coating and defining a SiO_2 cladding layer and SU-8 waveguide between the LEDs and PDs.

3. Results and discussion

All the interconnects show stable PD responses as a function of the LED current, as shown in Fig. 2(a). The interconnect with the 20 μm-wide LED has the highest response and CTR when the LED current is less than 1.6 mA, and that with the 50 μm-wide LED has the highest response and CTR when the LED current exceeds 1.6 mA. The power consumption of 50 μm-wide LED can be even less than 1 mW when the PD response reaches 0.85 μA. The PD response and CTR for the interconnect with 50 μm-wide LED at different PD voltages are depicted in Fig. 2(b). The peak CTR increases from ~0.9‰ to 1‰ when PD voltage changes from 0 V to -4 V. The dark currents of PDs are less than 0.1 nA under zero PD bias and increase to 2 nA under the reverse voltage of -4 V. Considering that the PD response current is > 0.5 μA when LED current exceeds 1 mA, the signal-to-noise ratio of our interconnects will be larger than 250. Comparison of the PD response between interconnects with and without the SU-8 waveguide is shown in Fig. 3(a). The responses decrease by about 60 times when the SU-8 waveguides are absent, indicating that > 98% light collected by PDs is guided within the waveguides. Reverse-direction optical interconnect is also demonstrated with the 70 μm-wide PD acting as a light source and the 50 μm-wide LED acting as a detector. Both forward and reverse directional interconnects show a similar response at the same light source current density, as shown in Fig. 3(b). Digital data transmission is also tested with a simple setup. Periodic voltage pulses with duration of 1 μs are injected to the LED and voltage pulses with similar duration are produced on the PD (results not shown here). Higher transmission speeds are expected to be achieved when our testing conditions are improved.

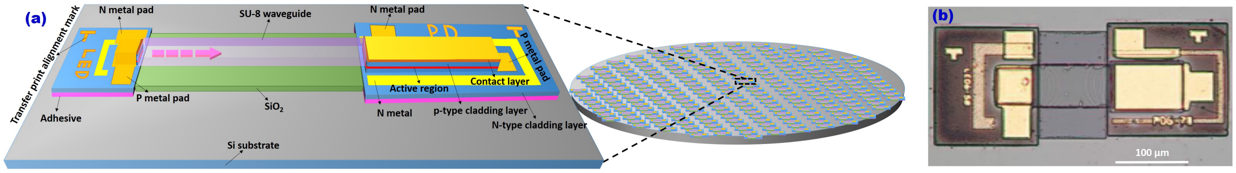

Fig. 1. (a) Schematic map of the on-chip optical interconnects on silicon wafer. (b) Microscope map of interconnect with 50 μm-wide LED

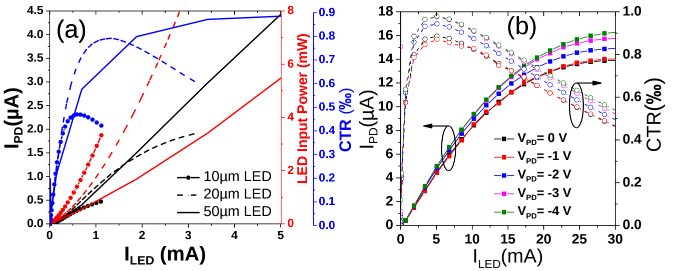

Fig. 2. (a) PD response (black), LED power consumption (red) and CTR (blue) for interconnects with 10 μm-wide (solid with symbols), 20 μm-wide (dash) and 50 μm-wide (solid) LEDs. (b) Responses and CTRs under reverse PD voltages.

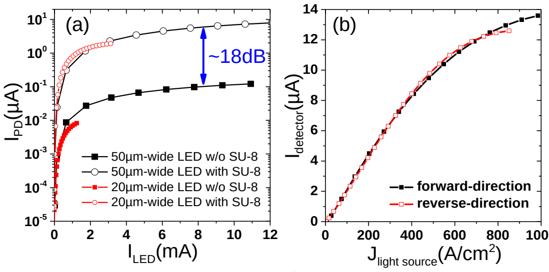

Fig. 3. (a) Comparison of PD responses between interconnects without and with SU-8 waveguide. (b) Bi-directional interconnect responses.

4. Conclusion

We have presented a compact optical interconnect of a LED to a PD integrated on Si by transfer printing. Static and dynamic data transmission is demonstrated with low power consumption. The advantages of its efficient light coupling, bi-directional interconnect and easy heterogeneous integration over traditional free-space edge-coupled LED-to-PD interconnect make it very suitable for applications like on-chip opto-isolators.

5. Acknowledgements

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