Hybrid Photonic Integration and Plasmonic Devices: New Perspectives for High-Speed Communications and Ultra-Fast Signal Processing

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Abstract: Hybrid photonic integration allows to combine the complementary advantages of different material platforms while maintaining the processing and scalability advantages of monolithically integrated systems. Here we give an overview on our research in the field of hybrid integration, combining multi-chip approaches on a package level with hybrid on-chip integration using both back-end-of-line (BEOL) and front-end-of-line (FEOL) processes.

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1. Introduction

Photonic integrated circuits (PIC) are key to a wide variety of applications, ranging from high-speed optical communications to metrology and sensing and further to ultra-fast signal processing. Over the last years, tremendous progress has been made in large-scale on-chip integration of optical devices, and several platforms have reached industrial maturity. However, these circuits mainly rely on monolithic integration concepts, where all devices are realized within the same material system. These enable highest scalability, but the performance of the resulting systems is often limited by the underlying material system. A prominent example is the silicon photonic (SiP) integration platform: From a technological point of view, silicon represents an excellent material system, enabling large-scale fabrication by mature CMOS processes along with monolithic co-integration of photonic and electronic circuits. From a functional point of view, however, silicon falls short of distinct properties that are indispensable for a wide variety of devices. As a consequence, performance of all-silicon devices is often limited, e. g., in terms of speed, energy efficiency, or device footprint.

In this paper, we give an overview of our progress towards hybrid integration of photonic systems that combine the distinct advantages of different integration platforms while maintaining most of the processing and scalability advantages. To this end, we combine hybrid multi-chip integration on a package level with hybrid on-chip integration using both back-end-of-line (BEOL) and front-end-of-line (FEOL) processes.

2. Overview

Regarding package-level hybrid integration, we have demonstrated that direct-write two-photon lithography lends itself as a viable tool for connecting photonic chips of different materials – either by three-dimensional (3D) free-form single-mode waveguides, so-called photonic wire bonds [1] – [4], or by facet-attached beam-shaping elements such as micro-lenses that allow for highly efficient coupling with relaxed alignment tolerances [5], [6]. We have demonstrated the viability of the concept by realizing multi-chip transmitter modules that combine silicon photonic modulators with InP-based laser-sources in highly integrated assemblies [7] [8].

To merge the advantages of different material systems in a BEOL approach, we have established the concept of silicon-organic hybrid (SOH) integration that combines silicon photonic waveguides with organic cladding materials. By using theory-guided design principles, these organic materials can be tailored to provide functionalities complementary to those offered by the underlying SiP circuitry [9] – [12] . This approach is particularly well suited for overcoming the intrinsic absence of second-order nonlinearities in crystalline silicon by exploiting highly efficient organic electro-optic materials, thereby outperforming conventional all-silicon depletion-type *pn*-modulators both in terms of speed and energy efficiency [9]. SOH devices have been demonstrated to exhibit in-device electro-optic coefficients well above 300 pm/V, leading to voltage-length products down to 0.32 Vmm. This enables high-speed communications at peak-to-peak drive voltages as low as 140 mV_{pp}, and energy consumptions of only a few fJ per bit [13]. The ultra-fast response of the electro-optic cladding materials enables small-signal modulation at frequencies beyond 100 GHz [14] and generation of on-off keying (OOK) data signals at 100 Gbit/s [15] [16]. We have further demonstrated generation of advanced modulation formats such as 16QAM at record-low energy consumption, and with symbol rates (bit rates) of up to 100 GBd (400 Gbit/s) transmitted on a single wavelength and a single polarization [17] – [19]. The extraordinarily low drive voltage of SOH modulators allows operation of the devices directly from standard output ports of field-programmable gate arrays (FPGA), without external amplifiers or digital-to-analog converters, even for generation of higher-order modulation formats such as 16QAM [20]. SOH electro-optic modulators can also be used in optical metrology, enabling, e.g., high-performance frequency shifters that exploit the concept of single-sideband (SSB) modulation [21]. Note that the SOH approach is a versatile concept that goes far beyond electro-optic modulators. We have also demonstrated SOH lasers [22] that exploit doped light-emitting organic materials, as well as highly efficient SOH phase shifters with liquid crystals (LC) as a cladding [23].

Regarding hybrid FEOL integration, we combine semiconductor-based dielectric waveguides with metallic nanostructures that support plasmonic wave propagation. These devices feature ultra-fast carrier dynamics, thus enabling signal processing at THz bandwidths. More specifically, we have demonstrated the concept of plasmonic internal-photoemission detectors (PIPED) that exploit photon-generated hot carriers transmitted across potential barriers at metal-semiconductor interfaces [24]. The devices combine short carrier transit times with ultra-small parasitic capacitances and can hence be used as photomixers for generation and homodyne reception of continuous-wave radiation at THz frequencies [25]. Expanding upon our work on SOH devices, we have also shown that organic electro-optic materials can be combined with plasmonic waveguide structures [26] [27], thus merging BEOL and FEOL hybrid integration. While the length and the efficiency of these plasmonic-organic hybrid (POH) modulators is limited by optical losses, the devices stand out due to their small footprint and their large electro-optic bandwidth [9].

In summary, we believe that hybrid integration on different levels of optical systems allows to combine the distinct advantages of different material systems and integration platforms. These apporoaches can hence pave the path towards photonic-electronic circuits for ultra-fast signal processing at THz bandwidths.

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