Photonic Integrated Circuits (PICS): From InP to GaN-based Solutions

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Abstract

Advances in InP-based photonic integrated circuits (PICs) from the first practical (commercial) system-on-chip (SoC) realization to current state-of-the-art are discussed. The extension of these to photonic ICs to the visible and near-ultraviolet spectrum using GaN-based semiconductors promises significant applications in optical communications, sensing, and quantum solutions.

INTRODUCTION

Modern electronics began with the invention of the transistor and the discovery of minority carrier injection [1]. The invention of the integrated circuit (IC) and the scalable nature of semiconductor technology [2, 3] have drastically transformed our modern world because of the ability of transistor and semiconductor technology to continually increase the functionality, performance, and reliability of solid-state circuits, while reducing their size, power, and costs. This scaling has been exponential, resulting in integrated circuits today that contain over 50 billion transistors per chip with a cost per transistor of <0.1 microcents. A key value of the integrated circuit is the ability to realize these improvements by eliminating the need to discretely package and assemble individual devices or smaller circuits by providing the device and circuit connections via semiconductor batch and wafer scale processing.

The development of the semiconductor laser [4], the semiconductor alloy laser [5], and the associated viability of compound semiconductor alloys [5] led the groundwork for the possibility of extending the electronic integrated circuit concept to photonics. This was first proposed by Miller [6] in The Bell System Technical Journal:

> *This paper outlines a proposal for a miniature form of laser beam circuitry…Photolithographic techniques may permit the simultaneous construction of complex circuit patterns…if realized…economy should result.*

Over the past 50-plus years since this proposal, there have been numerous research demonstrations of PICs. However, the economic value derived from an integrated component oftentimes does not outweigh the cost of the integration itself, which has limited the commercial success and development of PICs. To date, the introduction and scaling of PICs have been primarily driven by their use for optical communications applications.

This talk will review key PIC developments and advances that have resulted in the current state-of-the-art, including the ability for PICs to create value to enable new system architectures and applications. In addition, barriers and enabling technologies for future generations of PICs will be discussed as well as key elements to enable the more ubiquitous use of PICs in optical communications and other emerging applications. These advances will require significant innovation in chip, packaging, and assembly technologies.

INP-BASED PHOTONIC ICS FOR OPTICAL COMMUNICATIONS

Some of the earliest commercial PICs for optical communications were introduced ~30 years ago with the development of InP-based electro-absorption modulated lasers [7]. The commercial impact of PICs has substantially increased with the introduction of InP-based widely tunable lasers [8], and more recently, InP-based dense wavelength-division multiplexed (DWDM) transmitter and receiver system-on-chip (SoC) PICs operating at 100 Gb/s [9],

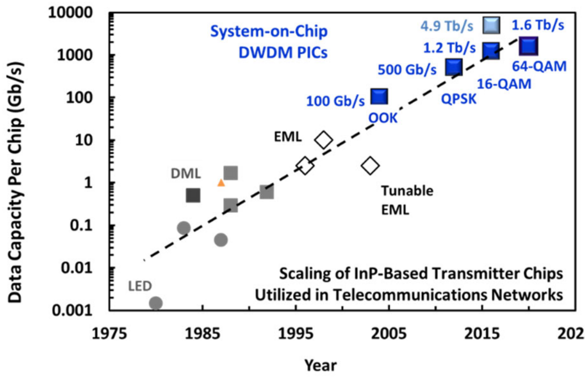

Fig. 1. Scaling of the data capacity per chip in commercial optical networks for InP-based transmitter chips. The data capacity per chip has doubled an average of every ~ 2.2 years (fit to the data) for the last 35+ years enabled by the employment of photonic ICs. Since 2004, commercial SoC DWDM PICs have been essential to this scaling (dark blue). A recent research result has demonstrated a SOC DWDM PIC capable of 4.9 Tb/s capacity (light blue) [11].

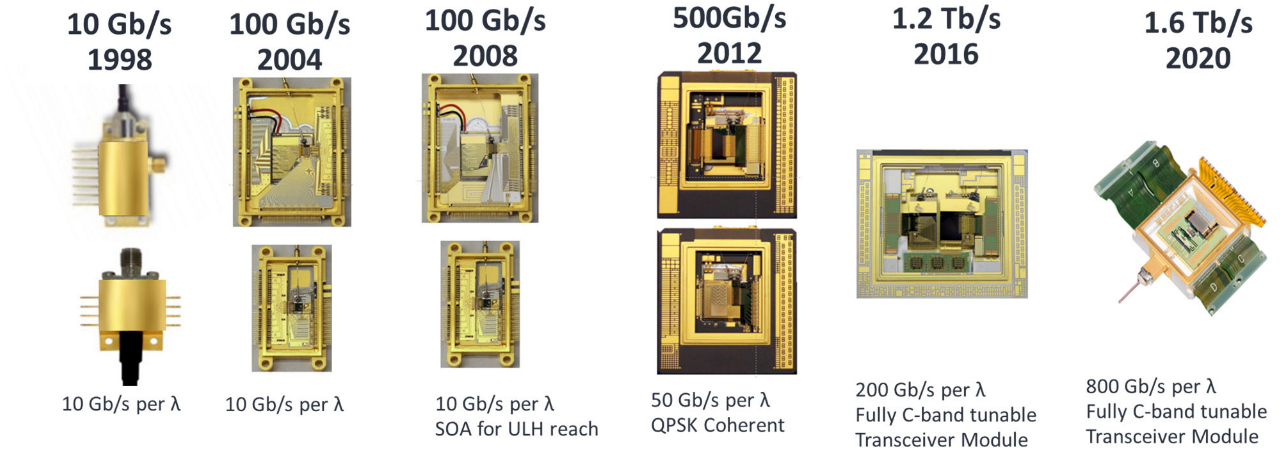

Fig. 2. Scaling of six generations of DWDM transmission modules. The commercial deployment of multi-channel DWDM SoC photonic ICs has enabled the scaling of total bandwidth per module by 160x in roughly the same footprint versus 10 Gb/s EMLs which were deployed circa 1998 (images shown to scale).

500 Gb/s [10], 1.2 Tb/s [11, 12] and 1.6 Tb/s [13]. The progression of these advances is shown in Fig. 1 and Fig. 2. These InP-based DWDM transmitter and receiver PICs integrate all optical functions required for a complete DWDM channel as well as integrating multiple of these channels onto a single monolithic chip for each transmitter and receiver. The largest scale of these commercial PICs integrates over 400 functions onto a single monolithic chip [11,12]. The highest performance PIC operates at >100 Gbaud and 800 Gb/s per wavelength [13], with research devices operating at>150 Gbaud and 1.2 Tb/s per wavelength [14].

GAN-BASED PHOTONIC IC TECHNOLOGIES

The visible and ultra-violet (VU) spectrum offer further significant opportunities for photonic ICs for emerging applications in sensing (environmental, health/medical, imaging, etc.), atomic/quantum devices and circuits (atomic clocks, magnetometers, gyroscopes, etc.), and communications (underwater and very lower power inter-chip and intra-chip communications). These applications have been made possible by the revolution in the realization of high-performance GaN-based light-emitters and laser diodes [15-17]. Despite these advances, there exists a lack of very high-performance VU spectrum sources which can be integrated on a full-function photonic IC (PIC) platform. Specifically, narrow-linewidth / low-phase noise, high-power, tunable laser sources that can be integrated with high-Q tunable resonators, filters, amplifiers, detectors, and modulators that operate across the VU spectrum are needed to enable transformative impacts.

While tremendous advances have been made in the development and realization of light-emitting diodes and laser diodes in the VU spectrum through the development of GaN-based alloys, several inherent challenges have limited the development of PICs in this spectral regime. These challenges include: the ability to realize very low-loss waveguides, the low-loss / low back reflection integration of passive waveguides with active devices, high-performance single frequency sources, the integration of multiple active regions on to a photonic IC, and the integration of high-Q (and tunable) resonators with engineered reflection spectra. These limitations arise from a number of inherent challenges in the GaN-based materials, including the reduced index contrast between the different constituent InGaN, GaN and AlGaN alloys, the limited ability to integrate the full range of alloys of AlGaN and InGaN into a single device structure due to high lattice and thermal expansion mismatch, the lack of high-quality selective area growth and butt-joint regrowth techniques to integrate multiple III-Nitride alloys on a single chip, and the inability to realize buried devices structures by regrowth (e.g., for buried heterostructure and buried ridge waveguides and active devices). Shortcomings on III-Nitride fabrication techniques to produce ultra-smooth etched waveguide sidewalls are increasingly an issue for violet and ultra-violet high-performance devices as scattering losses substantially increase with reduced wavelength (Rayleigh scattering loss being proportional to the inverse 4th power of the wavelength). In addition, the challenges of realizing crack-free integration of low-index dielectrics and integrated (buried) low-order grating structures further limit the realization of VU spectrum high-performance sources and PICs.

To overcome these GaN-based challenges, new fabrication techniques need to be developed. One such technique is Crystal Heterogeneous Integration (CHI), a next-generation wafer bonding technology that enables the large-area integration of III-N substrates with low-optical loss as well as low-resistance at the wafer-bonded interface for the integration of n-type layers. This technique enables the

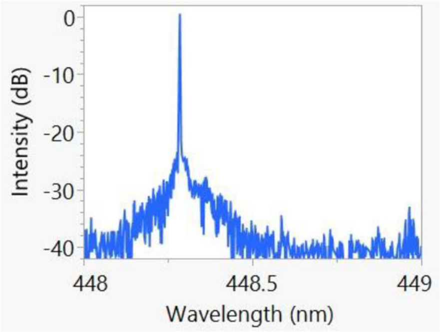

Fig. 3. Single-frequency emission spectrum of a GaN-based distributed feedback (DFB) laser using a first order grating [21]. Such sources an important building blocks for GaN-based photonic ICs.

realization of a new GaN-based PIC platform to integrate III-N actives and low-loss SiN-based passive waveguides. SiN-based waveguides have been recently shown to exhibit low losses in the range of 0.09-0.2 dB/cm in the 450-460 nm regime [18-19]. Furthermore, this low-loss SiN waveguide technology has also shown to be capable of the realization of high-Q resonators with a Q>9M at 461nm [20]. The new GaN-based PIC platform solves the problem of integrating these low-loss waveguides (which typically have an effective index (n_{eff}) in the ~1.7-2.1 range) with III-N active devices with an effective index of 2.2-2.6 and enables active-passive transitions with design insertion loss of <0.2 dB and with a design back-reflection < -60 dB.

This PIC platform is also compatible with the integration of recently developed single-frequency GaN-based distributed feedback (DFB) laser diodes [20-21] which utilize first-order gratings to achieve single-frequency operation with a side-mode suppression ratio (SMSR) >25 dB (see Fig. 3). These building blocks and PIC platform can enable important solutions in sensing and quantum science applications.

Another very important application for GaN-based PICs is intra-chip and inter-chip communications. The scaling of the total data capacity of advanced integrated circuit (IC) processor chips demands equivalent scaling of the input/output (I/O) of chip-to-chip interconnect. The I/O needs of these processors are scaling >50 Tb/s in the next few years. As a result, the industry is critically approaching the point wherein I/O power and density will limit the future processor scaling. Therefore, a transformative technology is needed to enable this continued scaling. Recently, GaN-based light emitters operating at >10 Gb/s [22, 23] have been demonstrated with an efficiency of <0.7 pJ/bit, which is inclusive of all the power required for the transmitter and receiver drive/amplify electronics and photonics [23]. In addition, these devices can be operated in large arrays for a high aggregate bandwidth (1 Tb/s demonstrated with 304 channels [24]). Furthermore, the ability to maintain high bandwidths (3 GHz) at temperatures as high as 290 °C has recently been demonstrated [25]. Unlike other optical communication sources, the high-temperature capability of these devices to operate at temperatures greater than the junction temperature of Si CMOS (approximately >125-150 °C) enables their placement in close proximity to the requisite drive electronics, eliminating the need for power-hungry SERDES, and significantly further reducing the power consumption. To date, these high-speed, high-temperature InGaN/GaN micro-LEDs have been realized in the surface-emitting configuration, coupled to optical fibers or fiber bundles [22-25]. However, the development of low-loss SiN waveguides and low-loss active-passive transitions with GaN-based active portends the capability to realize these devices in an edge-emitting configuration, which will further enable and expand applications for inter and intra-chip communications.

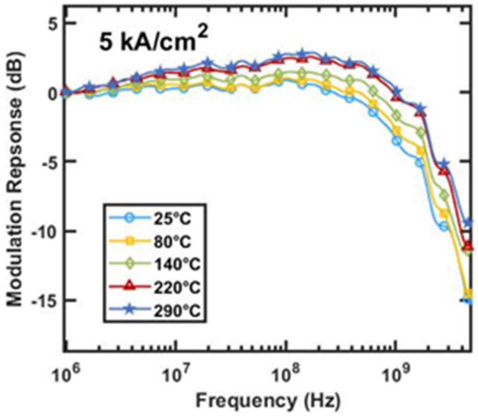

Fig. 4. Modulation response of InGaN/GaN micro-LEDs from 25°C to 290 °C at 5 kA/cm2 [25]. At 290 °C, the micro-LEDs exhibit >3.2 GHz bandwidth, which has been shown to be capable of >13 Gb/s transmission [24].

CONCLUSIONS

The era of photonic integration started with the advent of InP-based PICs employed for optical communications. Over the last 35+ years, these PICs have continued to scale in performance and complexity, enabling the exponential scaling of high-capacity optical networks and the communications revolution we have come to rely upon worldwide. GaN-based PICs will require significant new innovations to enable their realization, but in doing so, they can unlock new paradigms in optical communications, sensing, and the application of quantum sciences (for computing, communication, and sensing).

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