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FUTURE GENERATION OF SILICON PHOTONICS

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Abstract— **The recent progress is reviewed and future prospects of silicon photonics in next generation communication and computing systems are probed. Leverage is the many-billion-dollar complementary metal-oxide-semiconductor (CMOS) industry, the silicon photonics has promising prospects for realising very large-scale electronic and photonic integrated circuits with thousands of optical components and millions of transistors in the future to support very demanding integrated systems needs of next generation computing and communications. Due to recent investments by industry and government, silicon-based photonics have a chance of becoming "the" mainstream photonics technology. Purpose of this paper is to presents a survey of recent results found in journal articles and conference proceedings Emerging trends in silicon-based photonic components (waveguides, ultrafast modulators, switches, light sources, detectors, direct band-gap Si Glens/GeSn devices, photonic-crystal and plasmonic devices) are identified and discussed. Recently Si PICs and OEICs can operate anywhere within the 0.3 µm to 100 µm wavelength range enable to transceivers, on-chip processin, and interfacing with fibers or free-space light beams. Commercial state-of-the-art CMOS silicon-on-insulator (SOI) foundries are now being utilized in a crucial test of 1.55-µm monolithic optoelectronic (OE) integration and test sponsored by the Defense Advanced Research Projects Agency (DARPA). The preliminary results indicate that the silicon photonics are truly CMOS compatible.**

Index Terms— **Crystal, Ge photo-detectors, Infrared, Lasers, Opto-electronic integrated circuits, Photonic, Plasmonics, Photonic crystals (PhCs), Photonic integrated circuits (PICs), Plasmons CMOS, SiGe, SiGeSn, Silicon, Silicon lasers, Waveguides.**

I. INTRODUCTION

The goal of this paper is to set the stage for the invited and contributed papers in this issue by reviewing the history, the present status, and the future prospects of silicon photonics. This work emphasizes what has been done on the key components and their optoelectronic (OE) integrations. An attempt will be made to identify the emerging trends and remaining challenges.

Other authors in this Photonics West Conference 5730 will cover in detail the topics of optoelectronic integration, CMOS compatibility, optical MEMs, optical receivers, sensor applications, optical interconnect techniques, and nonlinear Raman effects. Rather than expounding upon these topics, I shall survey recent developments in silicon based photonic components including light emitters, lasers, and wave-guided components such as ultrafast electro optic modulators. This results taken from the literature and conference proceedings are presented in this paper. The paper focuses upon photonic structures that are amenable to Si-based optoelectronic integration.

A. *Silicon Raman Lasers*

The papers in this special issue reveal the progress that has been made in the fields of Raman lasers, PhCs, fast modulators, LEDs, photo detectors, micro resonators, plasmon optics, quantum-cascade structures, photonic-circuit integration, and OE integration. The development of the silicon Raman laser, mainly by the groups at UCLA [1] and Intel Corporation [2], was a dramatic milestone in the history of silicon photonics. Although this laser has low gain per unit length in its initial versions, the device is fully integrateable and offers tenability by design, that is, by the choice of alloy composition x in the waveguide core made of $Si_{1-x}Ge_x$, or by the use of higher order Raman shifts in the resonator. Looking to the future, it seems likely that performance improvements will be made in lowering the intensity threshold for optically pumped lasingand in migrating the wavelength of the operation toward the 3–5-μm region. The main drawback of this laser is its need for optical pumping (it takes a laser to make a laser). Electrically pumped lasers are usually more desirable in OE chips.

B. *Erbium–Silicon Lasers*

Barrios and Lipson have simulated the 1550-nm emitting properties of an electrically driven resonant-cavity LED consisting of Er-doped SiO2 situated in the central slot of a rib-wave-guided micro ring resonator [3]. Biasing of lateral P+-doped regions inside and surrounding the ring gives MOS excitation of the active slot material. These authors predict efficient electroluminescence coupled into the adjacent SOI channel waveguides, and they say the device has potential for lasing.

When rare-earth ions are implanted into an amorphous SiO2 layer containing Si nano crystals, an efficient LED can be made by injecting electrons into the oxide using biased P- and

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N-silicon layers sandwiching the thin film [4]. The researchers at ST Microelectronics boosted the directionality of Er:Si LEDs to attain laser-like 1540-nm emission from a vertical, resonant cavity LED employing Si/SiO2 distributed Bragg reflectors [4]. They say the laser is within reach.

Physically, the rare-earth doping is an "extrinsic" or guest–host effect whose strength is limited by the concentration of ions. Extrinsic is a disadvantage because the number of rare earth ions per cubic centimeter is much less than the number of Si atoms per cubic centimeter. Having said that, it should be denoted by A. Polman has achieved 1550 nm lasing in Er-doped (2×1019 cm−3) 15-μm diameter SiO2-toroids mounted on silicon, although this laser was optically pumped at 1480 nm [5]. The remaining technical challenges in making an electrically pumped room-temperature Er:Si laser are: 1) obtaining adequate electrical conductivity in the oxide/Si-nano crystal medium and 2) constructing an ultrahigh-Q laser resonator. Because considerable talent is focused on these problems, the challenges will probably be met.

C. Direct-Band gap SiGeSn/Ge/GeSn Hetero structure/QW Devices

The development of the GeSn alloys for photonics was pioneered by H. Atwater, Y.-H. Xie, E. Fitzgerald, and several others. In 1993 [6] and in a patent [7], I proposed that tensile-strained layers of Ge upon GeSn would have a direct band gap, and that strain-balanced multi-QW structures made of alternating Ge and GeSn nano layers are a basis for direct bandto- band photonic devices. J. Kouvetakis' research group at Arizona State University (ASU) has become a leader in the epitaxy of Sn-containing Group IV alloys. A relaxed buffer of GeSn or SiGeSn can be grown directly upon a silicon substrate and the top surface of either "virtual substrate" is an excellent template for the subsequent growth of MQWs because there are very few defects at that surface. Regarding hetero structure band-offsets, the theory of J. Menendez shows that the band alignment is Type I between Ge QWs and GeSn barriers when the buffer is SiGeSn (but it is Type II when the buffer is GeSn). This Type I prediction has been verified experimentally [8].

A recent patent [9] shows that Si-based Gee/GeSn MQWs (or hetero diodes having four or five layers) grown upon a SiGeSn buffer layer will give direct-band gap wells when the barrier and buffer compositions are chosen appropriately. The patent forms the conceptual basis for the 1.55-μm band-to-band laser diode project begun in 2006 at Quant Tera Corporation. Using Si based epitaxial Gee/GeSn MQW stacks grown at ASU, Quant Tera is investigating p-i-n pumped lasers.

D. PhC Devices

During the past five years, silicon PhC structures have become a special part of the silicon photonics technology. An extensive PhC literature has sprung up on both theory and experiment, and useful one-dimensional (1-D), 2-D, and 3-D silicon PhCs have been reported. PhC is can be engineered to yield devices with unique properties, such as negative-refraction lenses, superprisms, self-collimated waveguides, sharp waveguide bends, all-optical buffer memories, dynamic dispersion compensators, and nanoscale 3-D point-defect resonators that provide high Q and high concentration of the optical fields. The uniqueness adds value in PIC. In an experimental PIC, conventional Si strip (or rib) waveguides have been joined smoothly to the "unconventional" PhC line-defect waveguides.

Active devices are feasible too. For example, Altair Center LLC in cooperation with the University of Rochester is currently investigating a silicon-based PhC laser diode where in a PhC micro cavity forms the laser's gain region. Modulators have also been studied. By means of PhC "dispersion engineering" a carrier-injected PhC line-defect waveguide can be designed for the reduced group velocity in a recently experiment [10], produced a 33 ×reduction in the π-radian active length $L\pi$ as compared to the $L\pi$ of a conventional waveguide. Vlasov's group at IBM attained a 300-fold reduction in group velocity in the Si PhC line-defect waveguides [11]. Their waveguides were made in a CMOS facility. Jacobsen *et al.* [12] show that an SOI PhC line-defect waveguide, when strained by Si3N4 or SiO2, will possess a Pockel's electro optic field effect having 830-pm/V susceptibility at $\lambda = 1561.5$ nm.

These results suggest that the PhC devices can be a part of the high-performance chip-scale PICs and OEICs in future. The viability of the PhC contribution will depend, whether the PhC waveguide losses can be kept acceptably low. Evidence for low propagation loss was obtained with a suspended silicon PhC membrane (clad below and above by air) that contains the waveguides [13], [11]. I believe that active SiGe material can be deposited in this slot to create the "smallest possible" p-i-n lasers, modulators, and photo detectors.

II. FUTURE PROSPECTS

The future cannot be predicted: one can only make educated guesses about it. I shall simply make a few extrapolations of the present trends.

Within a five-year time frame, it is likely that we will see the following:

i. True OE integration on CMOS in a stable 130-nm or 90-nm commercial process;
ii. Hundreds of photonic components and more than a million transistors on a monolithic OE chip;
iii. Cost-effective fiber-optic links using Si OE transceivers exchanging data at 10–100 Gb/s;
iv. Fast, cost-effective optical interconnection of computer chips;
v. Integrated Ge-on-Si photodiodes as the 1.55 μm detectors of- choice in PICs and OEICs;

vi. A room-temperature electrically pumped Ge/Si laser;
vii. A well-developed Ge/GeSn technology—both MQWs and hetero diodes—that includes 1.55-μm band-to-band laser diodes, LEDs, modulators, and photo detectors;
viii. Silicon laser diodes that rely upon Erbium ions or PbS nano crystals;
ix. Integration of silicon PhC devices into high-performance silicon photonic circuits;
x. Development of practical Si-based Group IV components for the wide infrared spectrum stretching beyond 1.6 μm out to 100 μm—components such as emitters, quantum cascade, detectors, and lasers;
xi. Ultra small, nano photonic Ge-in-Si p-i-n lasers, modulators, and detectors;
xii. Si-based photonic devices utilizing Group IV quantum dots or QWs.

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