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Nanoscale Light Sources for Optical Interconnects

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Introduction

This editorial is aimed at addressing two key aspects of nanoscale light sources: (1) low-power optical communication and (2) crystallographic defect engineering for monolithic integration with silicon. We will further discuss opportunities and challenges for nanoscale light sources for next generation, high density optical interconnect. Designing and prototyping light sources with sub light wavelength dimensions has been the topic of keen interest because of their versatility in optical communication. For example, nano light sources can operate at hundreds of GHz [1,2] which is not possible with conventional light sources [3]. In addition, power consumption in interconnects with these light sources can be reduced by omitting the modulator and using direct source modulation to encode optical data [4]. There are a number of nano light sources under investigation: (i) small photonic mode laser [5-9], (ii) plasmonic lasers [10,11] (iii) photonic-plasmonic hybrid lasers [12-15] and (iv) nanoscale LEDs [16,17]. Pros and cons of these nano light sources are discussed below.

Nano scale photonic mode lasers based on photonic crystals (PhC) have shown the most promise requiring the lowest threshold current due to the high cavity quality factor [8,9]. The main drawback of such devices is their relatively large foot print (~10 μm²) which makes them unsuitable for monolithic integration with Si (see discussion below). On the other hand, metal cladded plasmonic lasers which have sub light wavelength foot print are capable of achieving high optical confinement, but these suffer from optical losses in the metal. For this reason plasmonic lasers operate at higher threshold currents than what is expected from a scaled optoelectronic device [18]. As such, the threshold current for state-of-the-art laser is in the tens of μA's range for deep-sub-wavelength lasing modes [19]. Most successful demonstrations to date on plasmonic lasers have been conducted by optical pumping because electrical-pumping requires either low temperature operation or large mode size above the diffraction limit [3]. To address shortcomings of plasmonic lasers, hybrid mode photonic-plasmonic lasers, whose mode primarily resides in the low-index oxide layers instead of the gain medium, have been designed. However, the low optical confinement factor of the hybridized optical mode limits the optical gain [13,14]. The most attractive option for a nano light source appears to be a nanoscale LED for two reasons: (1) improved Purcell factor resulting from the small cavity volume requirement [1,20] and (2) no threshold current requirement. The downside of nano-LEDs is their limited power output.

Challenges

Output power

The minimum power required for a nano-LED light source should exceed the quantum shot noise limit (20 photons/bit) of a photo-detector for optical communication to maintain a bit-error-rate of 10^{-9} [21]. However, the state-of-the-art photodetectors have significantly higher power requirements [22,23] which poses challenge for nano-LEDs based optical communication. Nano-photo detectors with very low detector capacitance [24,25] have been proposed but such devices have not yet been successfully demonstrated.

Surface passivation

To achieve high Purcell factor and enable high modulation speeds, metal cavity devices, such as plasmonic devices require cavity dimensions on the order of 100 nm. Highly effective surface passivation is therefore required to achieve surface recombination velocity to <10^4 cm/s. Although successful passivation schemes have been demonstrated [26], process compatibility and long-term stability has not yet been studied.

Efficiency

Nano plasmonic devices inherently have higher optical loss in the cavity than conventional light sources due to smaller volume. So far the demonstrated power efficiency and quantum efficiency are still orders of magnitude lower than conventional lasers. Photonic crystal lasers and nano-LEDs, are better alternatives for higher efficiency [9,16].

Optical coupling

Efficient coupling into an adjacent on-chip waveguide is challenging for small light sources, due the impedance mismatch between the high wave vector mode inside the nanolaser and the lower k-vector of the waveguide. However, several groups have recently achieved improved coupling efficiency of ~70% [7,27,28]. This required significant simulation, design optimization, and experimental control.

Reliability

Even though the power output of a nanolight source is typically in the sub micro watt range, its power density is nevertheless higher compared to a conventional light source. The high power density/high current density may cause reliability issues, such as electro migration and device heating [29]. Additionally, reliability issues could arise due to mechanical and thermal stresses in a packaged product.

Line width

Nano lasers are prone to increased spectral line width due to enhanced Purcell factor. Therefore, such lasers may not be suitable for DWDM applications. However, CWDM application might be possible because wavelength multiplexing in this case is relaxed.

Opportunities

Nano light sources are an attractive option for highly scaled short-distance optical interconnects [4]. We identify two key opportunities

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for nanolight sources: (i) monolithic integration, and (ii) three orders of magnitude higher density in optical interconnects on a semiconductor IC.

Monolithic Integration on Si or SOI Substrates

Sub-light wavelength dimensions of nanolight sources enable monolithic integration with Si or SOI substrates in an unprecedented manner, i.e., the integration does not degrade the LED efficiency due to lattice mismatch related crystallographic defects. This is because the probability of a dislocation or other crystallographic defect existing in the active device area decreases super linearly as devices approach nanometer dimensions (Figure 1). A monolithically grown III-V nano light source on Si substrate was indeed fabricated and its performance was analyzed [30,31]. We stipulate that when these devices are miniaturized to dimensions that are comparable to or smaller than the spacing between crystallographic defects, it may be possible to avoid defects in a majority of these devices to achieve higher performance on silicon.

High density optical interconnects

As an example, Figure 2 shows a nano-LED integrated monolithically by growing either a patterned III-V or a patterned III-N based LED structure onto an SOI substrate. A low-capacitance (~30 aF) and high efficiency Ge PIN photodiode is required. Numerical simulations indicate that 50% EQE is achievable with such a detector [32]. A low-loss waveguide is preferred. Previously, a "etch-less" waveguide has indeed been demonstrated earlier using SOI (0.3 dB/cm) in conjunction with selective oxidation to obtain high quality sidewalls [33]. Near ideal transmission (up to 93%) could be achieved over a ~1 cm distance. For a more typical loss of ~2 dB/cm, the transmission efficiency of the waveguide drops to ~63% for a distance of ~1 cm, but it can maintain ~95% transmission efficiency for a distance of ~1 mm.

Based on the scheme shown in Figure 2, it can be postulated that the optical interconnect density with nano-LEDs can be increased by three orders of magnitude over the current density. For example, for a waveguide with ~70% coupling efficiency, a transmitter with an EQE of ~20%, and photon energy of ~1 eV, ~125 photons/bit will be required to generate charge equivalent to 0.3 V. This corresponds to energy consumption of ~0.12 fJ/bit for the nano-LED. We estimate that a nano-LED with a drive current of 5 μA can operate at 40 GHz which will correspond to average optical power of ~0.8 μW in the waveguide. This power level is over 3 order of magnitude lower

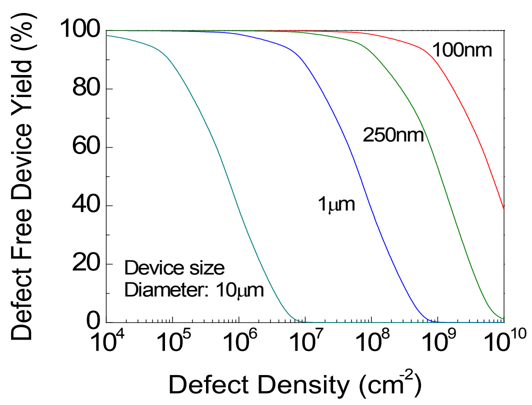

Figure 1: Defect free device yield of various sizes of devices as a function of defect density for III-V materials directly grown on Si substrate.

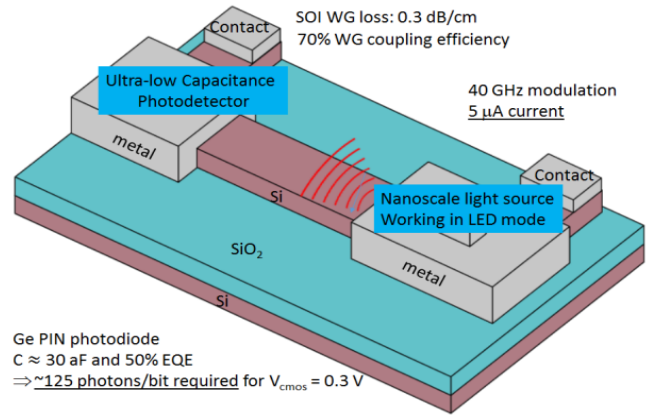

Figure 2: One possible scenario for an optical interconnect with a nanoscale light source, a low loss waveguide, and a low-capacitance photodetector.

compared to a standard conventional InP laser in use presently for optical interconnects. Therefore, nano optical devices in conjunction with monolithic integration has the potential to increase the number of chip-integrated devices from ~10^3 presently to 10^6 in future, notwithstanding the challenges described above.

Concluding Remarks

In summary, it is clear that nano light sources are a very attractive option for future optical interconnects for high band width optical communication. The possibility that monolithic integration of these devices on Si or SOI can be done without performance degradation will create a new paradigm for on-chip optical communication at short distances (<1 cm). Such integration can be scaled for high volume manufacturing making it cost competitive.

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