International Journal of Advancements in Electronics and Electrical Engineering– IJAEEE
Volume 4 : Issue 2 [ISSN : 2319-7498]
Publication Date : 30 October, 2015

Towards Lasing on a Silicon chip: Gallium and Its Alloy or Rare Earth Doped Gallium Nitride as the Solution?

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***Abstract*— Achieving effective solution for lasing on Silicon is a critical and important step for the successful implementation of Photonic Integrated Circuits in our quest to develop the next generation of ultrahigh bandwidth communication devices. In this overview paper various options of hybrid, monolithic and rare earth doping are discussed with the aim to offer the latest state-of-the-art on this topic. Monolithic integration of particular composition of Gallium and its alloys having the direct bandgap property and lattice constant similarity with silicon has been shown as promising. This is then compared with a Rare Earth doped Gallium Nitride approach as another possibility for the 'lasing on silicon' solution.**

***Keywords*—gallium alloys, lasing on silicon, integrated optics, telecommunication**

I. Introduction

In major initiative towards the development of Integrated Photonics the conventional waveguides are fabricated on Silicon (Si), this technological approach is known as silicon on insulator (SOI) [1]. Silicon is having advantages over the other semiconductors mainly due to the following reasons: (1) extensive availability and easy to process it in purified condition, (2) mechanical and thermal stability, (3) existence of state-of-the-art chip processing facilities. Thanks to the gradual miniaturization of silicon integrated circuits known as CMOS technology, in the last few decades, has been possible to improve the performance of computers at reduced cost. But this gradual miniaturization has led to some undesirable side effects for CMOS chips as the clock pulse width has also been gradually decreasing. The electrical cross-talk forced introduced relative "increases" of the total length of electrical connections per unit chip area in complex IC structures, RC delay due to increased metal line densities are some of the known drawbacks [2]. To overcome these difficulties, there is a global effort to find novel solutions for the development of improved CMOS fabrication techniques and photonic chip designs. At the same time, the means of communication via optical fibre has improved significantly. This has led to thoughts of utilizing the photonics 'into' semiconductor devices/chips for improving the speed of the signal processing. The key enabler is to have a 'chip level' lasing capability (i.e., the light source). At present, the lasing at the 'chip level' is provided by lasers formed of III-V semiconductors - a hybrid non-CMOS compatible solution, also more expensive compared to Si based devices. Moreover, the needed optical chip level alignment between III-V laser(s) and Si based waveguides are cumbersome, expensive, and also could be time-consuming. On the other hand, having an efficient light source integrated on Si chip will be ideal for supporting a chip-to-chip or within-the-chip communication.

II. Towards Lasing on Si

It is a great challenge to have integrated lasers on Si substrates. Si is an indirect band gap material for which emitting light is difficult to materialize. Free electrons tend to recombine with holes emitting phonons (heat) instead of light [3]. Moreover free carrier absorption hinders the population inversion which is a must for having stimulated light emission and gain. At the same time, the Auger recombination retards the density of emitted photon as shown in Figure 1 [2].

Scientists have been trying to improve the weak photo-luminance of silicon by using approaches such as Si nano-crystals [4] or using rare earth materials with Si [5] since 1990. But intense luminance is yet to be materialised.

A demonstration of lasing on Si has been achieved using Raman amplification in 2004 [6] however this approach requires another optical pump source for Raman

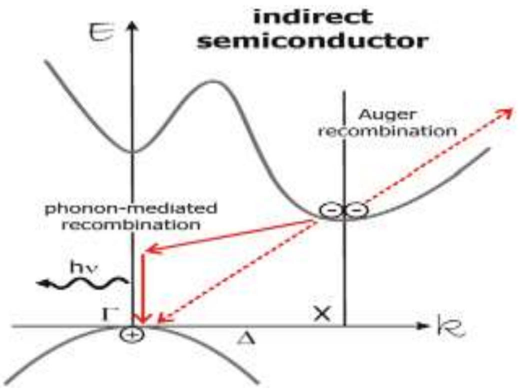

Figure 1. Indirect band-gap structure of Si [2]

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amplification and as such *practically* does not solve the described lasing needs in connection with Si waveguides. Alternatively, there is an option of fabricating individual lasers on a silicon die and then ensure an appropriate alignment. But this has drawbacks such as increased assembly time for attaching these lasers.

Some approaches of attached III-V based laser sources on a silicon photonic chip are schematically shown in Figure 2 [7]: The Off-chip and On-chip methods are the most straight forward approaches for injecting fibre-coupled laser light into a silicon photonic waveguide. One advantage of choosing the Off-chip method is its flexibility. The second advantage is a better thermal management of the photonic devices since the laser is separated from the chip. However, among disadvantages is the high cost of the laser and a large size of non-integrated packaging.

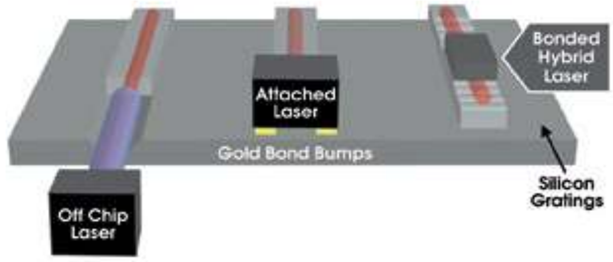

Figure 2. Three methods of integrating a laser on silicon devices (From left- Off-chip, On-chip and Hybrid lasers) [7]

A better approach seems the On-chip method where low cost lasers can be attached with the silicon chip. Still this approach has increased assembly time [7].

III. Gallium and Its Alloy on Si

A. *Hybrid Lasers on Si*

A fundamentally different approach is using so called hybrid lasers. Here a wafer bonding process is used. An unprocessed wafer made of Ga and its alloys (III-V materials) is bonded to silicon wafer which is patterned with optical waveguides. By the way of planar fabrication process, multiple lasers can be fabricated all at the same time across the wafer. One important advantage of this technique is that it does not need a laser alignment with the silicon waveguides since they are patterned before the laser fabrication. Here, the lasing is guided by the silicon waveguides but the electrical pumping and emission of light takes place in the quantum wells (AlGaInAs) of the III-V materials [7]. The optical gain can be varied by the adjustment of the height and width of the silicon waveguides. The bonding process is done at low temperature (about 300 ^{0}C) which allows the different thermal expansion coefficients of the two material types to ‘settle’ thereby avoid any kind of stress in the bonding outcome. In fact the key to this bonding technique is using the thin oxide glue that is used for bonding these two materials together [7]. The Figure 3 is a schematic diagram of such a laser device. With 65 mA of driving curent at room temperature, continuous wave (cw) having about 1.8 mW of output power and 12.7% quantum efficiency was experimentally observed [7].

However, these kind of hybrid devices have some disadvantages such as device's reliability and issues related to fabrication. Required different fabrication steps for Si chips and III-V lasers, including the alignment issues are not only expensive but also consume a lot of time. Moreover there is an upper limit on the integration density of lasers per a silicon chip [8]. A new concept named ‘monolithic integration’ [8] shows very good promise in solving the above problems.

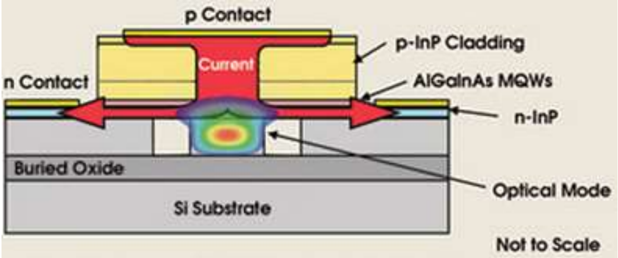

Figure 3. Schematic diagram of a hybrid laser [7]

B. *Monolithic Optoelectronics Integrated Circuits on Si*

There is a strong interest in growing monolithic integrated circuits on silicon substrates but as we have already shown it is quite difficult to achieve lasing ‘in’ silicon due to its indirect band gap characteristics. Therefore direct band-gap III-V materials such as GaAs and InP are studied intensively. But due to a large lattice mismatch between these III-V materials and Si, high dislocation densities are observed in the epitaxial films of III-V materials as seen in the Figure 4.

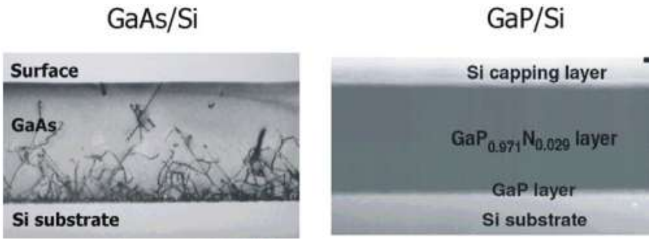

Figure 4. Transmission Electron Microscopy (TEM) images of lattice mismatch due to dislocations formed in the GaAs layer grown on Si (Left), Contrarily GaP/GaNP layers can be formed on Si without any threading dislocations [9]

The reason behind this dislocations can be understood if we study the energy bandgap vs lattice constant of III-V materials and Si (see Figure 5 [2]). We can see that GaAs and InP have lattice constants which are larger than Si by 4%. The question is how to suppress the formation of dislocations by optimising the epitaxial growth conditions in III-V layers. It can be also seen from the same plot that GaP (indirect band gap material) has a lattice constant very close to that of Si. At the same time, the Ga(NP) which is ternary material system can be grown on Si with lattice matching with the N content of only 2%. This was demonstrated by Hiroo Yonezu and et al. [9]. Base on this, one can grow the lattice matched direct band-gap materials on GaP then transfer them on Si substrates. This approach was undertaken as a new concept by the Material Science Centre of Philipps University Marburg in Germany.

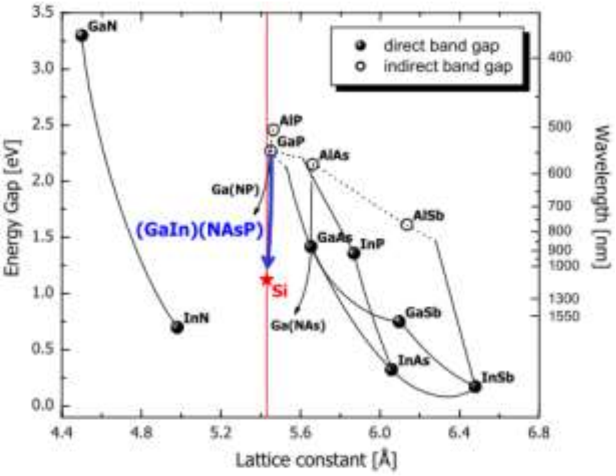

Figure 5. Transmission Electron Microscopy (TEM) images of lattice mismatch due to dislocations formed in the GaAs layer grown on Si (Left), Contrarily GaP/GaNP layers can be formed on Si without any threading dislocations [2]

Adding In, As and N helped to modify the band structure and transform it into a direct band-gap material. Here we note that the direct band-gap characteristics are important for optical gain and lasing action [2]. The combination of N with In and As helped with the important adjustment required for the compound material (GaIn)(NAsP) to be in line with the GaP lattice constant as seen in the Figure 5.

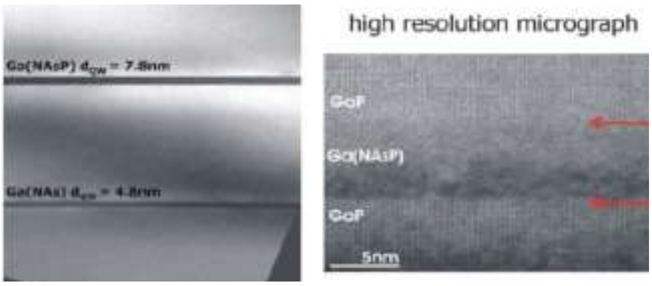

Figure 6. Transmission electron microscopy (TEM) images of Ga(NasP) quantum wells grown on GaP substrate [7]

The important task was to find the right composition of (GaIn)(NAsP) which supports the pseudomorphic growth of good quality films on GaP substrate showing direct band-gap structure and luminescence efficiency. Finally, Arsenic (As) rich nitride material Ga(NAsP) was introduced which can perform the above characteristics as repoted in [7]. The transmission electron microscopy (TEM) of Ga(NAsP) quantum wells grown on GaP substrate show the absence of any dislocations (seen Figure 6) [7]. This compound material shows direct electronics band structure for As rich composition. The thin multiple quantum well structure of Ga(NAsP) works as an excellent light emitter. Utilizing this material, a demonstration of electrically injected lasing action in a device at low temperature was shown by B. Kunert and et al. [10]. A forecast was also made on the development of such lasing mterials on Si microelectronics since Ga(NAsP) deposited on GaP can be transferred via deposition on Si because of similarity of lattice constants in between them [11, 9].

IV. *Rare Earth Doped Gallium Nitride*

We know that GaN is a semiconductor from a family of III-N compounds. These compounds cover a wide band-gap of energies as shown in Figure 7.

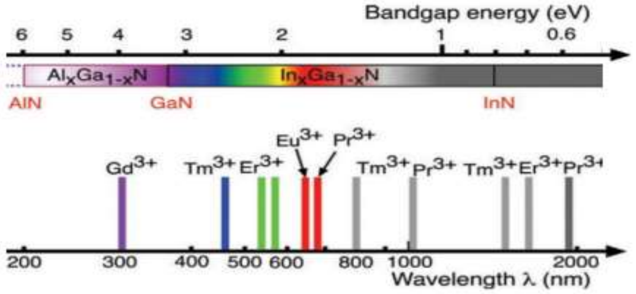

Figure 7. Associated band-gap energies of III-N compound semiconductors and emission wavelengths from selected transitions in rare earth ions [12]

We can see it is possible to emit photons in the Visible, Ultra-Violate and Infra Red regions using nitrides as host materials for Rare Earth ions [13]. Park and Steckl in [14] used Eu dopped GaN as the active medium. This consisted of multiple layers of AlGaN which were grown on Si substrate by Molecular Beam Epitaxy (MBE). Several AlGaN, AlN thin films were incorporated as buffers, strain compensators and bottom optical cladding. A 0.5 µm GaN active layer doped with 1 % Eu and AlGaN as top cladding was grown, the whole structure formed a planer waveguide [12, 14]. For the lasing action to happen, optical pumping by an N_2 pulsed laser (wavelength of 337.1 nm and pulsewidth of 600ps) was used. On the top surface of the waveguide, the laser beam was incident and under the pumping condition of 8 MW / cm^2 the emission from the edge was collected to analyse the emitting light characteristics (Figure 8). The red emission was observed which is mainly for the intra-4f transition of trivalent Eu^{3+} ions. The emission peak wavelength was 620 nm. The edge emission properties such as strong gain, polarization dependence, emission line-narrowing and threshold effect were seen. To measure the gain and loss characteristics, the respective techniques such as Variable Stripe Length (VSL) and Shifting Excitation Spot (SES) were used. Using VSL, the measured modal gain for the structure is shown in Figure 9. Threshold for stimulated emission was extrapolated to a value 117 $kWcm^{-2}$ and the modal gain obtained was 100 cm^{-1}.

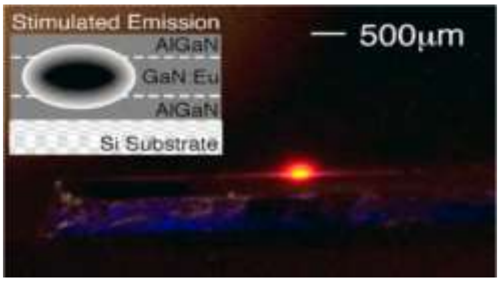

Figure 8. Emission from the edge of the GaN:Eu on Si structure. The inset shows the cross-section of the structure [14]

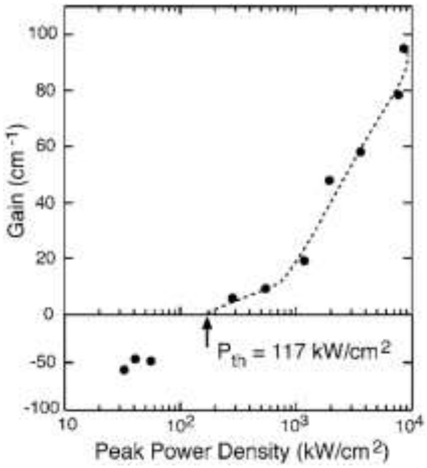

Figure 9. Gain and loss as a function of peak pump power density for GaN:Eu on Si laser structure [14]

However, below the threshold, a -50 cm^{-1} negative gain was observed which is similar to the modal loss value (~45 cm^{-1}) obtained by SES. Figure 10 shows a high resolution spectrum from a GaN:Eu planer waveguide structure where the cavity length is 350 µm. The spectrum has peaks equally spaced by 4 Å showing the presence of resonant-cavity modes. With the improvement in Gallium Nitride:Rare Earth (GaN:RE) growth, the cavity design and processing, a sufficient gain and loss reduction are expected. All the factors related to simulated emission as mentioned above indicated the action of visible lasing on silicon.

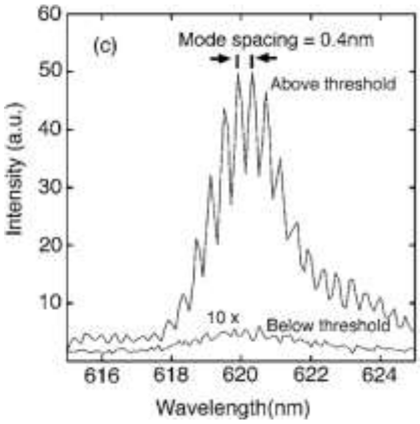

Figure 10. Spectrum of edge emission from 350 µm long cavity below and above threshold [14]

One advantage of using RE doping is that it provides a good option for sellecting different wavelength emissions needed for different applications [9]. Besides Eu dopant, the other researched rare-earth dopants are thulium suitable for generating 477 nm blue emission, erbium suitable for generating 537 nm to 559 nm and 1.5 µm emission [13].

V. Comparison

For selecting the lasing wavelengths, in Rare Earth (RE) doped GaN materials, different kinds of rare-earth dopants are chosen, whereas, in case of Ga alloy based compound semiconductors, different compositions and concentrations of elements in the compound semiconductor are chosen. Due to the severe temperature quenching and low level Rare Earth solubility at room temperature, the conventional RE doping in Si or GaAs semiconductors produces low photoemission [13], whereas, the electroluminescence emission of RE doping in GaN can be very strong and can be observed at the room temperature [13]. The thermal quenching of Er-doped semiconductor decreases as the bandgap increases [15]. Since GaN is a wide bandgap material, the thermal quenching of emitted light is not observed except well above room temperatures. Er^{+3} doping of GaN has produced strong photoluminescence in the IR region of 1.5 µm which is suitable for fibre optic communication [13]. Hence RE doping of GaN is a great alternative to Ga alloys based semiconductors for use in visible region and more importantly in the 1.5 µm band being used by telecommunication.

Using a co-doping approach of multiple RE ions, it is possible to achieve lasing on GaN:RE at multiple wavelengths simultaneously. This is not possible in alloy based compound semiconductors [12].

VI. Conclusion

Achieving lasing on Si chips is important for future development of ultrafast integrated CMOS compatible opto-electronic devices in order to help with addressing the ever increasing bandwidth requirements in the telecommunication networks.

Different methods such as off-chip, flip-chip, hybrid, and monolithic fabrication using Ga and its alloy based compound semiconductors are being investigated to support lasing on Si chips. Another method for implementing lasing on Si is RE doped GaN. Later one has a unique advantage offering lasing at different wavelengths by using RE co-dopants (option not available in the monolithic fabrication approach on Si).

In case of monolithic fabrication scheme, to overcome the lattice constant mismatch in the compound semiconductor different chemical compositions are added. In GaN:RE scheme, strain releasing buffer and cladding layers of different molar composition of AlGaN must be used.

In conclusion, from provided state-of-the-art research overview, it is evident that the GaN:RE approach for lasing on Si provides a good promise for developing future integrated CMOS compatible photonic devices for the next generation of telecommunication networks.

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