# Silicon Light-Emitting Device with Application in on-Chip Micro-opto-electro-mechanical and Chemical-opto-electro Micro Systems

Kaikai Xu, Lukas W. Snyman, Jean-Luc Polleux, Hongda Chen, and Guannpyng Li

*Abstract*—**The advances in silicon photonics related device development have been evolved into standard complementary metal-oxide-semiconductor (CMOS) technology in recent years. The emission of visible light (400-900 nm) by a monolithically integrated silicon p-n junction under reverse bias presents the silicon light-emitting device (Si-LED). As an integrated optical source, it is then developed for coupling light into the optic waveguide. Through the Monte Carlo and Rsoft BeamPROP simulations, the vertical emission, focusing, refraction, splitting and wave-guiding are also optimized using the same CMOS technology. Since the Si-LED, the $SiO_2$-waveguide, and the Si-photodetector can be monolithically integrated on the same bulk-Si substrate, a concise micro-opto-electro-mechanical systems (MOEMS) could be realized in the modern CMOS structural & integrated circuitry standard platform.**

*Index Terms*—**Silicon LED, micro-opto-electro-mechanical systems, waveguide, CMOS technology, monolithic integration.**

## I. INTRODUCTION

The exponential growth of global data volumes and associated data centers is outpacing the industry's ability to efficiently produce more powerful data processing integrated circuits in accordance with Moore's Law. The modern trend of deploying more parallel computers with higher capacity data storage solves the problem of lagging microprocessor speeds, but the resultant significant proliferation of separate data computing equipment in turn leads to a growing need for faster and more efficient communication between computers and data storage. Hence, the material of silicon based optoelectronics is considered to enable future computing systems with optical input-outputs co-packaged with CMOS chips to circumvent the limitation of electrical interface.

Despite of the indirect bandgap in Si, a series of viable Si light-emitting technologies have recently become available that enable the integration of light sources directly into Si CMOS technology [1]. The latest attempts for realizing optoelectronic systems in CMOS technology have until now mainly been focused utilizing wavelengths at 1550 nm, mainly because of the ease of design and fabrication of waveguides in this regime [2]. However, no effective optical sources and Si detectors are available at this wavelength.

Being different from the silicon photonics work that is done at wavelengths around 1550 nm, it is observed that visible light with a typical spectral distribution curve in the wavelength range of 365 to 689 nm is emitted by silicon p-n junctions both in avalanche breakdown and in breakdown by internal field emission [3]. The light emission implies that Si diode under avalanche breakdown condition is a potential light transmitter which can monolithically integrate with silicon electronic circuits using the standard S-CMOS process [4], since the light source is a silicon device. On the other hand, a need for developing shorter wavelength optical sources (~450 nm) in order to act as an optical clock pulses in next generation CMOS circuitry has been expressed [5].

If optical source, detector, waveguides, and sensors could be realized on the same CMOS chip at the visible wavelength range, various on-chip-based micro-photonic systems can be realized. Achieving these goals can lead to diverse low cost "all-silicon" opto-electronic systems, which will be the "smarter" and more "intelligent" CMOS chips of the future. These systems could lead to new products for especially the medical and bio world. Such a new field could be appropriately named "Si CMOS photonic micro-systems." These systems also do not require ultrahigh frequency bandwidths and the emission powers of these Si light-emitting diodes (LEDs) may be sufficient to sustain the operation of such systems. This can lead to many new products and open up new markets.

This paper reviews the Si-LEDs, which are fabricated in standard CMOS process with no change to the CMOS design and processing procedures, we have jointly realized in the past two decades. By coupling the device to a standard mode optical fiber, first interation optical communication between one CMOS device and a second is successfully constructed. A new technical approach is proposed to resolve the issue of optical properties with native interband electro-optical emission in Si. Finally, the potential applications of Si-LEDs

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into micro-photonic systems and MOEMS are furthermore highlighted as a conclusion.

## II. FIELD-EFFECT ELECTROLUMINESCENCE IN SILICON

The profile about the composition and structure of a gate-controlled diode based LED structure is shown in Fig. 1. It is a poly-Si gate p-channel MOSFET, with gate oxide thickness of 4000 Å. The width of the device is ~175.5 µm and the channel length is ~6 µm. The poly-Si gate thickness is ~400 Å [6].

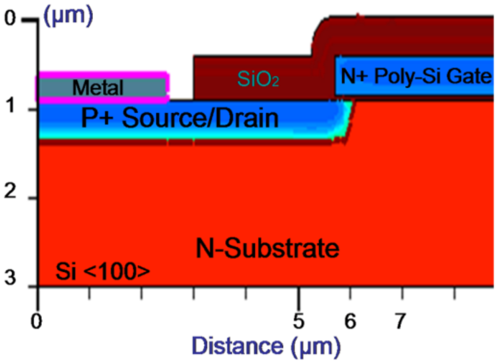

Fig. 1. Cross-section view of the a gate-controlled diode structure (i.e., one half of the Si-PMOSFET device)

In contrast, Fig. 2 shows details about the composition and structure of the planar Si *n*+*p* LED structure. The structure consists of a heavily doped The structure consisted of a heavily doped *n*+, $10^{19}$ $cm^{-3}$ doped layer of 0.3 µm thickness defined and realized in a 0.75~1.25 Ω•cm p-type substrate by means of appropriate ion beam implantation, masking and dopant activation procedures. Appropriate *n*-well guard-ring structures were placed on the periphery of the *n*+ region in order to ensure a uniform and planar breakdown at the planar *n*+*p* interface [7].

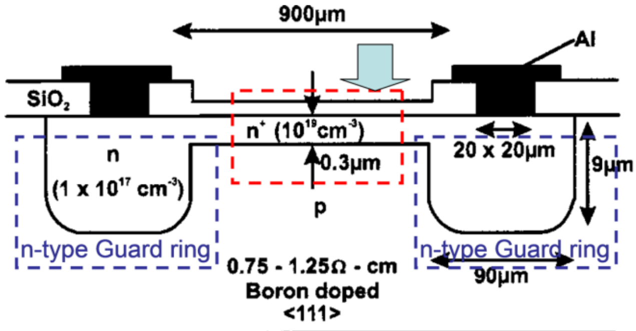

Fig. 2. Structural details of a Si *n*+*p* abrupt diode (after ref. [7]).

Further, Fig. 3 presents a modified structure. When a reverse bias voltage is applied between the inner *p*+ centroid and the *n*+ ring arrangement, a lateral and concentric electrical field is created between the *p*+ centroid and the *n*+ rings, which results in the creation of extended depletion layer at each *n*+*p* interface facing the *p*+ centroid. Due to the high doping concentration at the surface of the intersecting Si-$SiO_2$ interface, the light is emitted vertically from the device through the thin residual $SiO_2$ layer present on the Si surface [8].

## III. DESIGNING LATERAL WAVEGUIDES FOR CMOS STRUCTURES

The current CMOS technology can create a thin oxidation layer that is used as an isolation layer in the trench technology. If the layer is enhanced and followed by a layer of high refractive index material, such as Si nitride, interesting lateral optical conductors and waveguides can be constructed at the Si–over layer interface. Optical sources positioned at the trenches' edges enable optimum coupling of optical radiation into the trench waveguide. In a similar way waveguides can be fabricated in the outer CMOS layers.

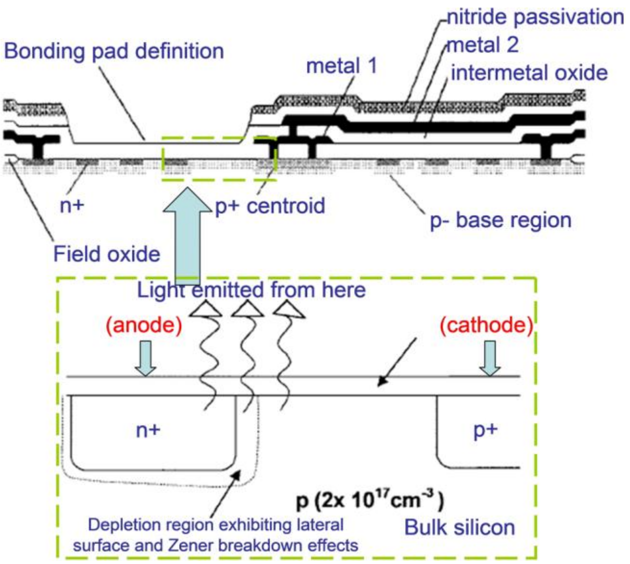

Fig. 3. Cross-section view of a Si-LED with diameter of 60 µm. Further design details present a schematic diagram showing the origin and the location of the light emission process at each *n*+ ring structure (after ref. [8]).

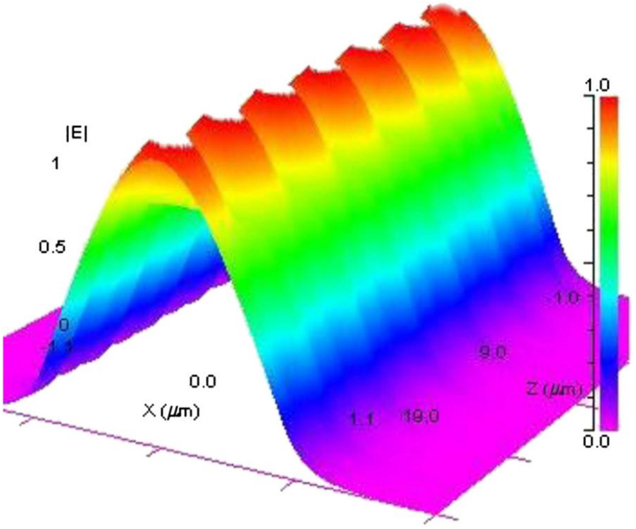

Fig. 4. Advanced optical simulation of the electrical field propagation in a 0.5-µm-wide Si nitride layer embedded in $SiO_2$ in CMOS integrated circuitry using finite element analysis and solutions of Helmholtz's equation. Multi-mode optical propagation at 750 nm is demonstrated over 20 µm distance with a loss smaller than 1 dB ·$cm^{-1}$ .

Advanced optical simulation software (RSOFT Beam PROP) is implemented to design and simulate specific CMOS based waveguides operating at 750 nm based on CMOS materials and parameters. This software uses an advanced finite analysis method where the volume is divided up into a large number of matrix elements. Helmholtz's equation predicts the optical parameters along the matrix based on the initially defined optical fields [9].

It is preliminarily shows that a multimode, as well as single mode wave-guiding can be achieved. Fig. 4 shows a three dimensional (3-D) view of the electrical field along the waveguide of a 0.6 µm wide Si nitride waveguide.

Multimode propagation is demonstrated with almost zero loss up to a distance of 20 µm. Multimode propagation in CMOS micro systems has the advantage of having a large acceptance angle for coupling optical radiation from a Si LED into and out of a waveguide. Our calculations show that a coupling efficiency of 0.38 can be achieved for a flat Si-emitting surface positioned at the edge of the Si nitride core of the waveguide. This is mainly due to the better refractive index matching between Si (3.76 at 750 nm wavelength) to Si nitride (2.00 at 750 nm).

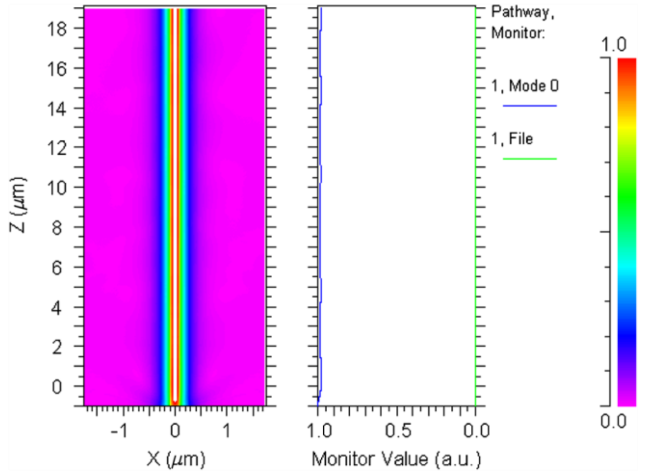

Fig. 5. Simulation of the optical field propagation in a Si nitride layer in CMOS integrated circuitry using finite element analysis and solutions of Helmholtz's equation. Single-mode optical propagation is demonstrated at 750 nm over a distance of 20 micron for a 0.2-µm wide, Si-oxide-embedded and Si nitride waveguide.

Fig. 5 shows the predicted optical simulation for a 0.3-µm diameter Si oxi-nitride waveguide embedded in Si oxide. The two-dimensional plot of the electrical field propagation along the waveguide shows clearly single-mode propagation. The calculated loss curve in the adjacent figure shows almost zero loss over a distance of up to 20 µm. The coupling efficiency into such a waveguide is, however, much reduced to values of about 0.05. Multimode to single-mode converter structures can then be used to increase the overall coupling efficiency into the waveguide.

## IV. APPLICATIONS OF SI DEVICES IN CMOS-BASED MICROPHOTONIC SYSTEMS

A hypothetical micro-photonic system is demonstrating in Fig. 6 consists of an Si-LED, a Si detector together with waveguides integrated monolithically in a CMOS structure. Wide area Si-LEDs are used in order to increase the total optical emission power into the waveguide systems [10].

Appropriate filtering by means of ring resonators, and enhanced phase contrast detection can be obtained by utilizing unbalanced Mach-Zehnder interferometers. Near the layout end, an opening is integrated in the CMOS over layers by post processed RF etching to enable gas or liquids to interact with the evanescent field of a waveguide section and introduces intensity and/or phase contrast changes.

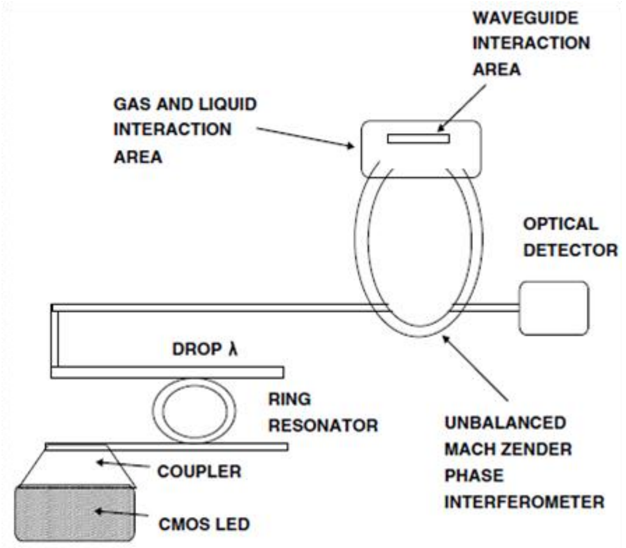

Fig. 6. Schematic diagram of a CMOS-based micro-photonic system that can be realized using an on-chip Si Av LED, a series of waveguides, ring resonators, and an unbalanced Mach-Zehnder interferometer. A section of the waveguide is exposed to the environment and can detect phase and intensity contrast due to absorption of molecules and gases in the evanescent field of the waveguide (after ref. [10]).

Hence, a complete micro-photonic sensor system can be integrated into standard CMOS circuitry. The added intelligence component, the lowering in cost and the increase in reliability of such systems can be significant. The source & detector and waveguide arrays can be arranged to find some performances in the emerging field like bio- and nanotechnology.

## V. ANALYSIS OF ELECTROLUMINESCENCE IN SI MATERIAL

Silicon is an indirect bandgap material, but light emission could be observed from reverse-biased pn junctions. Since electron-hole pair is produced during avalanche breakdown, some radiative recombination can occur. Both the electrons and holes can be heated by the electric field. The radiatvie transition between hot carriers emit photons larger than the bandgap. Hence, the luminescence during avalanche breakdown is characterized by a broad emission spectrum. Since the energy for impact ionization by hot carrier is about $1.5E_g$, the emission spectrum extends to ~ $3E_g$ (where the energy gap $E_g$ is of ~1.12 $e$V for silicon). This represents transitions from the hottest electron energy to the hottest hole energies. In this section, several attempts are made to understand the origin of light from avalanching silicon p-n junction, with physical model for the light emission.

Fig. 7 shows that, no matter what the detailed structure of the silicon pn junction is, it always emit light in a broad spectrum from 450 to 800 nm with characteristic peaks at 500 and 650 nm [4].

Based on the classical electromagnetic theory, the kinetic energy of electron is released in the form of photons if an electron collides with a singly charged Coulombic center. The electromagnetic field is quantized as a photonic system.

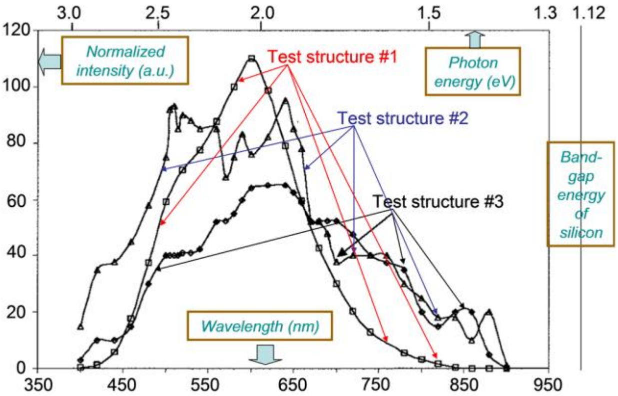

Fig. 7. The spectra of the emitted light from the several types of silicon pn junction measured at the avalanche breakdown operating point.

Using Maxwell's equation in which the particles are the sources for current and charge distribution, the exact field at the position of the particle can be obtained from self-consistent calculation. The kinetic equation becomes

$$\frac{\partial f_\alpha}{\partial t} + \vec{v} \bullet \nabla f_\infty + \frac{q}{m}\left(\vec{\mathrm{E}} + \vec{v} \times \vec{\mathrm{B}}\right) \bullet \nabla_v f_\alpha = \left(\frac{\partial f_\alpha}{\partial t}\right)_{coll} \qquad (1)$$

where the left hand side contains only averaged quantities and the so-called collision terms on the right hand side contains all microscopic interactions [11]. The collision term for momentum transfer can be evaluated for drifting Maxwell distribution functions, and it is found that

$$\int_{-\infty}^{+\infty} d v_\alpha m v_\alpha \left(\frac{\partial f_\alpha}{\partial t}\right)_{coll} = \sum_\beta m_\alpha n_\alpha v_{\alpha\beta}\left(\mu_\alpha - \mu_\beta\right) \qquad (2)$$

where $\mu_\alpha$ and $\mu_\beta$ are the drift velocities of species $\alpha$ and $\beta$ [12].

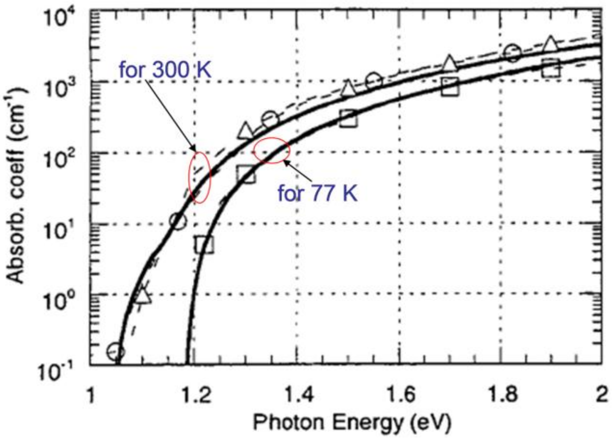

Fig. 8. Optical absorption coefficient of silicon.

Since the photons with energy above 1.08~1.12 *e*V (i.e., the silicon energy bandgap lie) are absorbed, the electroluminescence spectra peak shit shown in Fig. 7 should be related to the optical absorption coefficient that has been given by the Macfarlance absorption model [13] , which is also characterized in Fig. 8.

$$\alpha_{absorption} = A \cdot \left[ \frac{\left(h\nu - E_g - \overline{E_{pn}}\right)}{1 - \exp\left(\overline{E_{pn}}/kT\right)} + \frac{\left(h\nu - E_g + \overline{E_{pn}}\right)}{\exp\left(\overline{E_{pn}}/kT\right) - 1} \right] \qquad (3)$$

It is further interpreted the spectra obtained under avalanche breakdown conditions, but the multitude of the mechanisms described above shows a great divergence in the interpretation of spectra and proves that the origin of the light emission is not yet well defined and remain in debate [14].

## VI. CONCLUSION

This paper describes the manufacturing and production processes of a micro-system in modern nano-scaled MEMS technology. The potential applications of 600 to 850 nm Si LEDs and 600 to 850 nm-based waveguides in CMOS-based optical link toward the micro-photonic systems and MOEMS has been demonstrated. The physical mechanisms responsible for the photon emission identified at some extent to further clarify that the self electro-optic effect of the silicon light source could be further improved for the realization of flip-chip bonded monolithic CMOS optoelectronic smart pixels, in which Fig. 9 presents three different types of structure [15].

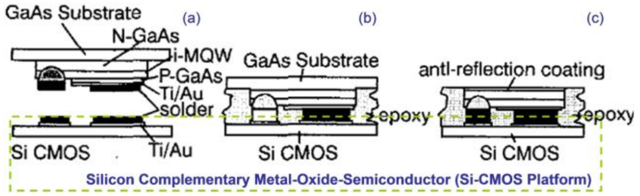

Fig. 9. The flip-chip bonding fabrication procedure.

Finally, the study of multi-terminal low-voltage CMOS Si-LEDs with emission efficiency enhancement is suggested to be analyzed in more detail in near future [16].

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