As today’s complementary metal oxide semiconductor (CMOS) technologies are scaled down to below 65 nm, conventional metal lines carrying signals in an integrated circuit face increasing challenges. As a short-term solution, the semiconductor industry adopted copper instead of aluminum for interconnects due to its low resistive behavior and good electromigration property. However, issues such as delay degradation, interference, and power dissipation will remain for metal interconnects as we further scale down feature sizes.

The International Technology Roadmap for Semiconductors (ITRS) suggested optical interconnects as one of the viable solutions to continue to improve on device performance. Optical interconnects usually require less power to operate for distances involved in off-chip communication and are also naturally resistant to electromagnetic interference. The industry has been accustomed to using direct band gap emitters for fiber optic communication for many years. Most optical interconnect applications prefer to use light emitters based on III–V or other direct band-gap materials due to their higher quantum efficiency. Researchers have mostly considered multi quantum well (MQW) optical modulators and vertical cavity surface emitting lasers (VCSELs) for inter-chip data communication.

MQW modulators are formed by a series of quantum wells contained within the intrinsic region of a reverse biased PIN (p-type, intrinsic, n-type) junction. These modulators require that an external laser beam be brought onto the modulator, which can be considered a disadvantage. Application of an electric field across the wells changes the absorption coefficient of the well material according to the quantum confined Stark effect resulting in modulation of the external beam incident on the device. The light beam is reflected by a mirror at one end of the PIN stack and routed using optics. However, bringing in the external beam and rerouting the reflected light complicates the opto-mechanical packaging of modulators.

VCSELs emit light in a cylindrical beam vertically from the surface of a fabricated wafer and offer significant advantages compared to the edge-emitting lasers used in fiber optic communications devices since they can be placed on top of a chip in large numbers (i.e., thousands). Both MQW modulators and VCSELs can provide a high number of connections between chips for inter-chip data communication and offer large data rates. These emitters need to be integrated to silicon CMOS as it is the base very large scale integration (VLSI) technology due to its low cost and widespread use. Monolithic integration of VCSEL and MQWs on Si CMOS has been problematic due to lattice mismatch. Hence, these optoelectronic devices need to be fabricated separately and hybrid bonded to silicon chips or wafers using flip-chip technology to
reduce any parasitic effects. This requires major changes in conventional fabrication process and an increase in the production cost.

On the other hand, the distances involved in inter-chip and intra-chip communications are considerably short. For these applications these bright direct band gap emitters are not necessarily required. Instead, we could use silicon-based optimized light emitter sources for such small distances due to the availability of high sensitivity Si-based detectors. Although the efficiency of such silicon emitters is poor, their ability to modulate at GHz frequencies makes them a good choice for many applications, including optical interconnects and optical contactless logic testing. The use of silicon photonics would be advantageous due to the direct integration of optoelectronic devices into microelectronic circuitry with single CMOS processing. The benefits are reduced cost of manufacturing and increased yields, since we could avoid the expensive compound semiconductor technologies.

Researchers have investigated light emission from silicon since the 1950s, but it had not been investigated seriously until the early 1980s. The possibility of using the silicon light emitter in an all-silicon optical interconnect application has been the main motivation. The silicon material itself is a poor emitter of light. Quantum efficiencies for silicon light emitters in the range of $10^{-4}$–$10^{-5}$ have been reported in the literature as compared to direct band-gap materials having quantum efficiencies of the order of $10^{-1}$.

Several parameters, such as doping profile, layout, and processing must be adjusted in order to achieve maximum efficiency and to make certain applications feasible. With the development of efficient silicon light emitting sources, many new applications would be enabled. These include fiber optic transmitters, high-speed intra- or interchip optical interconnects, inexpensive optical displays, biomedical sensors, and optical contactless logic testing.

Silicon LED theory

In 1955, Newman reported visible light emission from reverse biased silicon p-n junctions. It has been known since then that a silicon p-n junction emits visible light under the avalanche breakdown condition. Interest has grown in the consideration of silicon light emitting devices as a potential candidate for optical interconnect applications. Starting in the 1980s, porous Si light emission was investigated by many researchers due to its strong light emission in visible. However, stability of these devices has become an issue. More recently, attention has been drawn to Erbium doped silicon devices as they can provide high efficiencies comparable to a conventional LED diode.

Silicon is an indirect band-gap material, thus an inefficient light emitter. In silicon, the minimum energy in the conduction band and the maximum energy in the valence band occur at different values of electron momentum. Electrons and holes can only recombine if a lattice vibration (phonon) with the correct amount of momentum is present. We can classify the photon generation mechanisms into two main categories (see Fig. 1):

a) The interband (band to band) mechanism with direct and indirect recombination of conduction band electrons and valence band holes. The mechanisms in this category cannot produce photons with energy smaller than the energy band gap. The indirect process is commonly assisted by phonons.

b) The intraband (single band) transition involves only one type of carrier electrons or holes within their respective energy band. The transition can be direct or indirect. The indirect process is assisted by phonon or impurity ions.

The following are the reasons why we should consider silicon as a good candidate for a luminescent source for chip-chip optical interconnects and contactless logic testing:

- The approach uses standard silicon IC processing and requires no extra processing on the chip.
- The low light emission efficiency may be acceptable, since the light can be detected at a short distance away by a high sensitivity system.
- The total luminescence exhibits time stability and resistance to temperature variations.

Despite its relatively low electro-optical conversion efficiency, it will be shown here that sufficient light is generated for the applications of interchip/intra-chip optical interconnects and optical contactless testing.

Silicon light emitter structure

The silicon LED devices developed in this research utilize the electroluminescence characteristic of avalanche silicon p-n junctions optimized for photon emission. Light-generating test structures were fabricated through MOSIS using 1.5-$\mu$m CMOS fabrication run. Only standard silicon dopants (boron and phosphorus) have been utilized without
requiring any other substrate. The fabrication resulted in a silicon p-n junction that emits visible light when operated in avalanche breakdown. The light emitter was 75 μm by 75 μm in size. Fig. 2 shows the “postage-stamp” test structure and a close view of light emission.

Light is emitted over a wide range of wavelengths in visible and near infrared range from such structures, but with a low efficiency. Several parameters (e.g., doping profile, layout, and processing) must be adjusted to achieve maximum efficiency. Fig. 3 shows the emission spectra measured at three different spots shown in Fig. 2. The spectral peak is at \(-2\ \text{eV}\). The emitted light is observed to be stable and has been utilized as a light source for this research.

The spectral peak intensity showed a linear relationship with breakdown current from 2 mA to 10 mA. Reliability studies of photon emission on the silicon emitter devices also indicated that there are no adverse effects after ac, dc, and temperature-stressing tests are done.

Researchers measured a 20-GHz modulation speed for a reverse biased Si p-n junction biased in the avalanche breakdown region. Since switching induced hot carrier luminescence in silicon has also been measured in speeds exceeding 10 GHz, the switching time for Si LEDs is on the order of picoseconds.

**Si-based optical interconnect**

In designing the transmitter circuit, the voltage swing above and below the breakdown voltage of the Si LED should always be as little as possible, thus reducing the current drive needed by the Si diode capacitance. The logical driver circuit needs to be designed in such a way that the silicon p-n diode will switch on and off quickly with the driver signal and it should not load the signal source. Switching the LED diode current completely on and off results normally in a slow system. Therefore, some current should be always sent through the LED even with a logical “0” (Fig. 4).

The current mirror formed by M10 and M11 puts the silicon LED above its threshold by setting the LED bias current to 2 mA and putting the junction in avalanche breakdown. Transistor M9 couples the signal to the LED structure and provides an additional current of 4 mA for the Si LED structure. M9 is driven by the inverter string formed by M1–M8, which provides the gain, and ensures that normal logical circuits can drive the device.

**Receiver circuit and feasibility**

In this section, it will be shown that sufficient light is generated from optimized silicon LED structures for the purpose of optical interconnect and high speed contactless testing. Experimental results will be demonstrated in next section.

Assuming all photons generated arrive at the photodetector with an applied bias current of 6 mA for the emitter device, the total number of electrons/second, \(n_e\), can be found after dividing bias current by electronic charge \(q = 1.6 \times 10^{-19}\) and \(n_e\) turns out to be \(3.75(10)^{16}\) electrons/sec. Next, given the quantum efficiency \(\eta = 2.22(10^{-5})\) the number of photons per second, \(n_p\), can be calculated as \(8.325(10)^{13}\) photons/sec.

On the other hand, the energy of a photon is given by:

\[
e = \frac{hc}{\lambda}
\]

where, \(b = \) Planck’s constant, which is \(6.626(10^{-34})\) Js, \(c = \) speed of light, which is \(3E8\) m/s and \(\lambda = \) wave-length of light in meters.

![Fig. 2 Silicon light generating test structure.](image)

![Fig. 3 The spectra.](image)
For a given wavelength, the optical power can be calculated by multiplying photon energy by the number of photons per second \( n_p \). The emission spectrum of a silicon LED that is developed in this research is in the 400–800 nm range. Assuming the emission wavelength is 570 nm, which is yellow, the optical power of the LED is calculated as 0.29 \( \mu \)W.

The required transimpedance gain of the receiver can now be calculated for a typical silicon PIN detector. For a typical responsivity (photocurrent generated per watt of optical power) value of 0.6 A/W, the photocurrent value \( I_{ph} \) corresponding to the silicon output power would be 0.174 \( \mu \)A.

The feasibility calculation can be verified assuming typical noise characteristics of commercially available silicon receivers. For example, the Hamamatsu silicon photodiode amplifier module C5658 can be considered at the receiving end. This detector has an upper detection limit over 1 GHz and noise equivalent power of 0.5 pW/Hz\(^{1/2}\).

For 1 GHz modulation frequency, the optical power level corresponding to unity signal-noise ratio (SNR = 1) is calculated as 16 nW. Considering a Si LED source power of 290 nW and assuming a 5 dB coupling loss for the optical link, the incident power on the detector reduces to 92 nW. In this case, the signal to noise ratio SNR is calculated as 5.75. This result shows that still sufficient light is generated from such silicon light emitting structures. The light emission efficiency is acceptable as it can be easily detected with detectors made in silicon technology. Furthermore, higher emission efficiencies have been reported by researchers for silicon emitters making all-silicon based optical interconnect systems possible.

**Experimental results**

In this scheme, the light is generated by biasing the Si LED at avalanche breakdown voltage, then coupled through a fiber cable made of SiO\(_2\) and detected by a Si based avalanche photo-diode (Fig. 5). The generated light is coupled to a 50 \( \mu \)m conventional multimode, graded-index, optical fiber cable. The receiver used consisted of a Si p-i-n avalanche photo detector (APD) and a transimpedance amplifier that were manufactured using a conventional fabrication process. The light emission was coupled to the fiber by directly holding one end of the fiber directly over the silicon emitter as shown in Fig. 5.

The reverse biased silicon p-n junction (Fig. 2) operated in avalanche mode at 2 mA of current. This experiment utilized the Hamamatsu avalanche photodiode module C5460–01, which had a gain of 1.5E8 V/A. The silicon LED was modulated up to 100 kHz frequency limit of the detector. Fig. 6 compares the resulting waveform at the detector output to the original waveform driving the silicon light-emitter. The result shows good correspondence to the input waveform.

The receiver circuit is not expected to limit the development of silicon based optical interconnects since researchers have shown operation of Si-based receivers in the gigahertz range.
Results demonstrate the feasibility of an all silicon optical interconnect using an optimized silicon emitter for light emission. The bandwidth of this system is only limited by the receiver amplifier.

The power requirements for optical interconnects are also found comparable to those of conventional metal interconnects for off-chip interconnects. All Si-based optical interconnects can address the challenges associated with metal interconnects without resorting to any other fabrication process.

For long on-chip interconnect lines such as data buses and clock distribution networks, metal interconnect power dissipation becomes very high with increasing circuit frequencies. For such interconnect distances, all silicon optical interconnects can also provide a solution and become an alternative to metal interconnects.

With advanced technologies and higher doping densities, a lower power requirement is on the horizon for avalanche breakdown resulting in power savings on the silicon-based light emitters. Progress has been shown recently in the development of silicon-based light sources, waveguides, and detectors that are the required components for on-chip optical interconnects. Optical communication within a chip is possible by direct optical coupling through the Si substrate, or via an integrated waveguide. All silicon optical interconnects have the potential to outperform metallic interconnects and can solve the communication bottleneck in high-performance integrated circuits.

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