

High Speed Light microLEDs for Visible Wavelength Communication

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ABSTRACT

Visible wavelength data communication is of interest for short distance chip-to-chip interconnects and free-space links such as Li-Fi, where modulated sources are incorporated in lighting systems. For the former, both high modulation bandwidth and low power consumption are critical. At Avicena, we have developed efficient high-speed light-emitting structures capable of multi-Gb/s NRZ modulation, which operate down to a few microamps of drive current. We have demonstrated a high speed and low energy optical communication links using these novel devices.

Keywords: GaN microLED, visible-wavelength communications, spatial-division-multiplexing

1. INTRODUCTION

Over the last 30 years, optical communication has replaced wires at ever shrinking lengths. Forty years ago, long haul data transmission in trans-continental links were the first to transition from wires to optical fibers, while today the boundary between optical to electronic data transmission has reduced to a few meters. Generally, across ICs, circuit boards, and within a rack, data links are still over copper, while high speed links between racks, across data centers and longer, have switched to optical. These optical links operate mostly in the infra-red part of the spectrum on account of the material properties of optical fibers and availability of semiconductor laser sources.

Data transfer and interconnects remain a bottleneck at shorter distances for many reasons. The input/output of a chip is generally confined to the periphery of the die, and as the die becomes larger, the perimeter to area ratio shrinks, chocking the data flow. The limited number of pins out of a package, along with signal integrity and interconnect power consumption issues have required the use of ever more heroic serializer-deserializers (SerDes) and electronic equalization circuits to put highly multiplexed dataflows into a limited number of wires. However, on-chip data communication occurs at the clock speed of the chip, which has levelled off to a few GHz on account of the slowing of Moore's Law.

For nearest neighbor die-to-die interconnects that are just a few mm long, SerDes can be avoided by using a relatively slow bus, but at the price of a very high number of data lines to reach the required throughput density (Gbps/mm). To support such a high line count, costly silicon interposers are used within packages to connect chiplets together. For example, High Bandwidth Memory (HBM) chips, which are frequently co-packaged with GPUs or CPUs, have a data bus that is about 1000 lines wide, but operate at a relatively slow few Gb/s rate per lane. Since the impedance is not controlled over the lines, the link length for HBM is limited to a few millimeters, forcing chips to be packaged side to side.

Fundamentally, optics is capable of very high parallelism. For example, the transmission of images through lenses is a form of extremely wide parallel data transmission. Over the last 30 years, quantum well modulators, VCSELs, and other surface-emitting optical devices have been candidates for highly parallel and very low power per bit chip-to-chip transmission¹. In addition to lenses, imaging fiber, with very high core-count, has also been used to efficiently transfer parallel data². Highly parallel optical communications also requires optical devices that are "impedance matched" to transistors. Lasers and 50 Ohm terminated modulators typically require milliamps of current and about 1V swing. Transistors, on the other hand require far lower current and the same swing voltage and are thus "impedance-mismatched" to optical devices. What is critically missing to exploit this parallelism is a low power moderately fast light source that can easily be integrated with silicon and operates at current levels more suited to transistors.

Displays made from GaN MicroLEDs, lifted off and bonded to glass or silicon, are aimed for mobile phones, watches, virtual-reality eyewear and other applications. Compared to back-lit liquid crystal or OLED displays, they are brighter and more reliable, and can exhibit better color. Very high pixel count displays have been demonstrated at various scales for these different applications. Relatively high-speed modulation has also been shown in these devices, mostly aimed at “Li-Fi” where the same device provides general illumination and data transmission³⁻⁶. In simple NRZ modulation, bandwidths on the order of 1Gb/s have been obtained in devices at very high current densities. With more complex modulation formats such as PAM4 or OFDM, up to 10Gb/s has been reported.⁷

There are various approaches to increasing the modulation bandwidth of GaN LEDs by optimizing various factors that affect speed. Generally higher carrier density results in faster recombination, so almost always LEDs are faster when driven hard. Therefore, most of the results in the literature for high-speed performance are given at high current densities. However, much of this speed-up is due to increased non-radiative recombination mechanisms, so operation at high current densities tends to come at the cost of quantum efficiency (QE). Of course, for LiFi applications, where brightness is also important, a high current density that is operating far into the “droop” region of the device also lowers the efficiency for lighting. But there are other key mechanisms that impact the modulation bandwidth, such as the built-in field of GaN quantum wells that decreases the overlap of the electron and hole wavefunctions in the quantum wells. This lower overlap lessens the recombination rate and therefore reduces the modulation bandwidth. This field is usually screened at high carrier injection levels, but the use of a non-polarized substrate can eliminate this built-in field completely. Rashidi et al.,³ for example, demonstrated InGaN LEDs on free-standing non-polar (m-plane) substrates with a 3dB bandwidth of over 500MHz at 10kA/cm². Reducing the active region thickness and barrier thickness are also purported to increase speed by increasing the uniformity of carriers in the quantum wells, with a report of 380MHz and 1GHz at 2.5kA/cm² and 5kA/cm² current density respectively.⁴⁻⁶ Of course, capacitance must be minimized, therefore smaller devices are generally used that are not limited by RC time constants.

Fundamentally, the speed of a microLED is determined by the carrier lifetime, while the QE of a microLED is the inverse of the radiative recombination lifetime divided by the total carrier lifetime. Therefore, there is a simple trade-off between QE and speed. For example, a material full of non-radiative recombination defects will make a faster LED than one that is extremely efficient. An LED typically has a peak in efficiency versus current density. At low currents, SRH recombination tends to reduce QE, while at high currents, droop is a combination of Auger recombination and/or carrier overflow.⁸⁻⁹ Though not previously reported in the literature, if the radiative recombination time is relatively fast at low current densities, the lower intrinsic efficiency of an LED at very low currents could result in higher speeds even at very low currents. This intrinsic trade-off between QE and speed can be improved by optimizing the structure, doping, “Coulombic enhancement” and cavity effects.

In this work we compare the performance of a proprietary speed-optimized microLED against a standard microLED optimized for QE and show that such a speed-optimized device is capable of about 3-5x faster response than what has been reported in the literature. Furthermore, we show that these high-speed characteristics can also be obtained at very low current densities, enabling extremely low power and reliable data links.

2. DEVICES AND PERFORMANCE

To investigate QE versus speed, identical structures were processed on both standard and high-speed epi design material, both with a peak emission wavelength of 430nm. We could therefore compare the relative QE of the high-speed design to the standard brightness-optimized wafers with roughly 80% internal quantum efficiency. This comparison with known standard material allows us to estimate the internal quantum efficiency of the high-speed design as the extraction efficiency of devices with identical processing is assumed to be the same. Knowing the speed, as measured by the S21 curves on a network analyzer, gives us the carrier lifetime, while the estimated quantum efficiency gives us the relative ratio of radiative transitions to non-radiative recombination. Thus, the two recombination rates can be used to explore the physics of the high-speed devices.

In all cases, the growths were on 6” diameter patterned sapphire substrates (PSS), with an n-type silicon-doped GaN buffer, followed by InGaN QWs and a thin magnesium-doped p-cap layer. The material was dry-etched and a transparent ITO applied to the surface and connected with Al metallization to small bond pads. A top n-type contact was made to the underlying n-GaN buffer. To minimize capacitance and improve isolation, the n-GaN was etched down to the sapphire substrate layer outside of the active areas. Various devices with sizes from 4um diameter to 32um were

fabricated and tested at different drive current levels. As previously mentioned, the processing was identical between the standard and high-speed wafers. The measurement was performed with a calibrated power meter with the same collection optics for all devices, and thus we assume the same optical collection efficiency for all standard and high-speed devices. Fig. 1 shows the relative QE of different size high speed devices compared to the standard wafer. The y-axis is normalized to the 80% internal QE of the standard material. As the figure shows, the parameters used to increase the bandwidth are reducing efficiency by about a factor of 2 at the peak. The low efficiency at lower currents is indicative of a high rate of non-radiative recombination compared to the radiative recombination at low currents. This is either due to an increased number of defects in the high-speed material compared to the standard wafer, increasing SRH recombination, or the defects in the high-speed wafer being more active. The peak in efficiency moves out to higher current densities as the device size is reduced. We assume this is due to surface effects and non-radiative recombination at the edges of the device.

The second plot shows the 3dB electro-optical bandwidth of the devices as measured by S21 on a commercial network analyzer. Also included are some sample points of high-speed devices reported in the literature. Devices from the standard wafer has a 3dB bandwidth below 500MHz at low current densities but reaches about 1GHz at about 7000A/cm². We observed some roll-off in speed at very high current densities, presumably due to poor injection efficiency.

Though a direct comparison to this work and devices in the literature is difficult to make on account of different wavelengths of operation and different QEs, our devices are clearly better optimized for speed. As seen in the right-hand section of Fig. 1, we observe much higher speeds than those reported in the literature at high current densities. But what is perhaps more significant is the relatively high-speed operation at low current levels. To our knowledge, this high-speed operation at low current densities has not previously been reported in the literature. We have a 3dB bandwidth of between 1.5GHz and 2GHz at current densities below 100A/cm². This matches the poor efficiency of the devices at these current levels, presumably due to high recombination rate from defects that are not saturated.

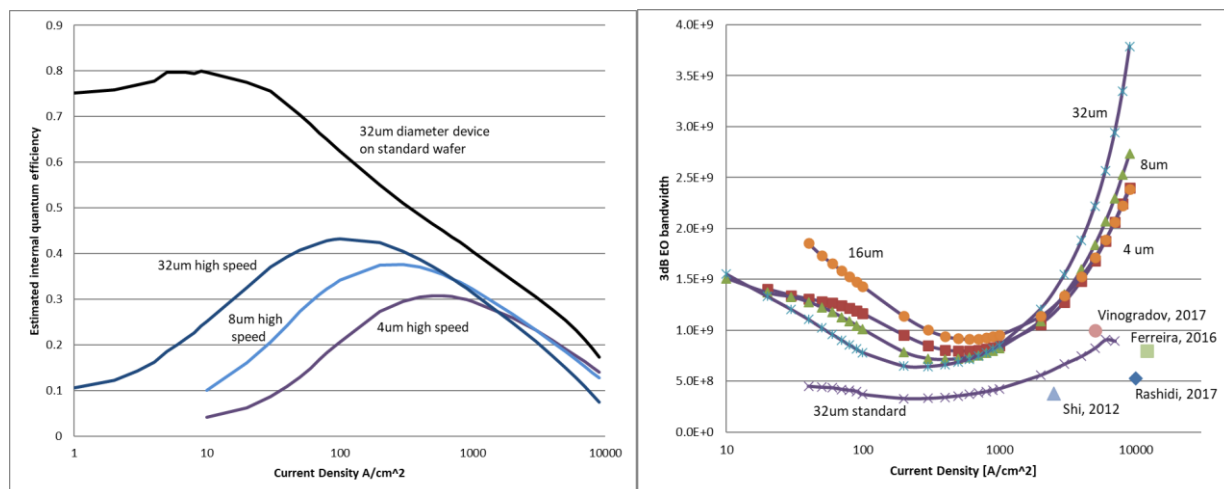


Fig. 1: Measured efficiency and speed of high-speed LED design compared to a standard production wafer optimized for QE. Devices optimized for speed are less efficient, but much faster. Individual points on the second plot are from references, giving different 3dB EO bandwidth data for a given current density.

3. DISCUSSION ON LED PERFORMANCE

As previously mentioned, there is a natural trade-off between speed and efficiency. Simply having material that is full of defects will give us higher speed, but at the price of lower efficiency. For chip-to-chip applications, some trade-off is reasonable. Perhaps a figure of merit should be the product of efficiency and speed. This is plotted in Fig. 2A below.

We can see that the high-speed design is about 30% better in this than standard material. Note that this figure of merit is relatively flat, with the device becoming faster when it is less bright. There is a peak at lower current densities, where operation might be beneficial.

One can decouple the radiative and non-radiative recombination rates in these devices. If the radiative lifetime at a given current is given by τ_r and the total non-radiative lifetime is given by τ_{nr} , then the radiative quantum efficiency should be equal to $(1/\tau_r) \div (1/\tau_r + 1/\tau_{nr})$ and the 3dB frequency should be proportional to the inverse of the total carrier lifetime: $(1/\tau_r + 1/\tau_{nr})$. Multiplying the two, and scaling appropriately, we can calculate and extract both the radiative and non-radiative lifetimes. Since we know the current density and the carrier lifetime, we can also calculate the actual carrier density in the quantum wells and plot these lifetimes as a function of the derived carrier density. These are shown in Fig. 2B for the standard wafer and the high-speed wafer.

For the standard wafer, the non-radiative recombination rate, a mixture of SRH, Auger, and carrier overflow is very low at low current densities, as evidenced by the high value for the lifetime. As the carrier density increases, this lifetime shrinks as non-radiative processes speed up. The slope gets very steep at high current densities, presumably due to Auger recombination where the lifetime goes as $1/n^2$. (The total recombination rate in the material goes as n^3 , but for a given injected carrier, the lifetime is $1/n^2$).

The radiative lifetime in the standard wafer also goes down at higher current densities, as we would expect it to go as $1/n$. Interestingly, the radiative lifetime is also short at lower current densities, presumably due to Coulombic enhancement. As a result of a relatively short radiative lifetime and also a high non-radiative lifetime at low current densities, LED efficiency has a peak at low injection rates. At higher injection rates, the increased Auger dominates and we see “droop.”

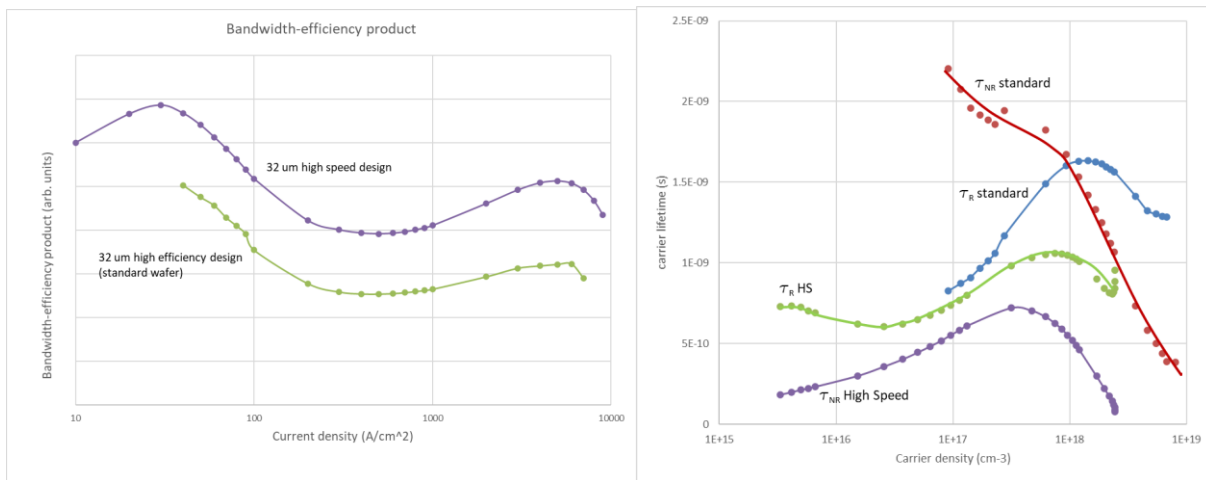


Fig. 2: On the left is the product of 3dB-bandwidth and relative efficiency between standard and high-speed designs, showing that it may be beneficial to operate in the low current regime. The radiative and non-radiative components can be solved, giving the plot on the right.

The high-speed wafer clearly has a different signature. The radiative recombination lifetime is relatively flat and falls due to $1/n$ at high carrier densities. The non-radiative lifetime is very low at low current densities, showing the presence of active defects, then saturates somewhat, and once again drops rapidly at higher carrier densities on account of Auger. The high non-radiative recombination rate is clearly responsible for the high-speed characteristics at low currents.

4. LINK DATA

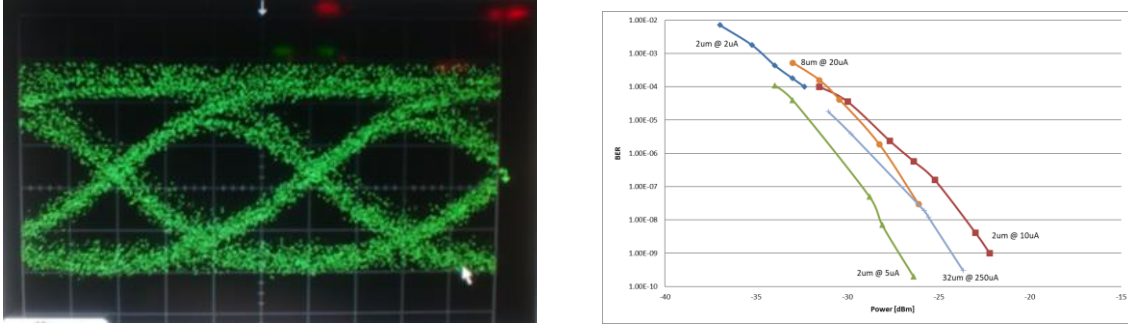


Fig. 3: Eye diagram of a 2μm diameter device running at 10uA of current at 1.25Gb/s. On the left are BER waterfall charts of different size devices running from about 2uA of drive current to 250uA.

High speed devices were fabricated as single element and arrays, some all in parallel, some individually addressed, and used for a variety of link tests. Unlike VCSELs with a threshold current, these microLEDs can be driven at very low currents and as described above, still operate at high speeds. Similarly, GaN devices have excellent high temperature characteristics and do not degrade substantially in performance or reliability when run at elevated temperatures.

To investigate the low power mode, arrays of different size devices were run at different currents through a standard BERT system. The light was detected with an APD and a ~1GHz bandwidth TIA. To get enough light at the detector, some of the devices were run in arrays, with the same current going to all the devices. The 2μm device was fabricated as a 10x10 element array, the 4μm in 5x5 and the 8μm in 3x3 format. The current reported is the value through an individual device. Fig. 3 shows the eye of a 2μm array device running at 10uA of current at 25C. The BER plot to the right shows expected link behavior.

The high-speed characteristics were measured with a pin detector and a 10GHz datacom-grade TIA. The eye diagram in Fig. 4 shows an open eye of an 8μm device running at about 5kA/cm². BER curves are shown for 4, 5, and 6 Gb/s NRZ at room temperature. The test was also performed at 105°C base temperature. The light output dropped about 30% compared to 25°C, but the BER curves actually improved as the speed of the light emitters increases with temperature, presumably due to increased recombination rate.

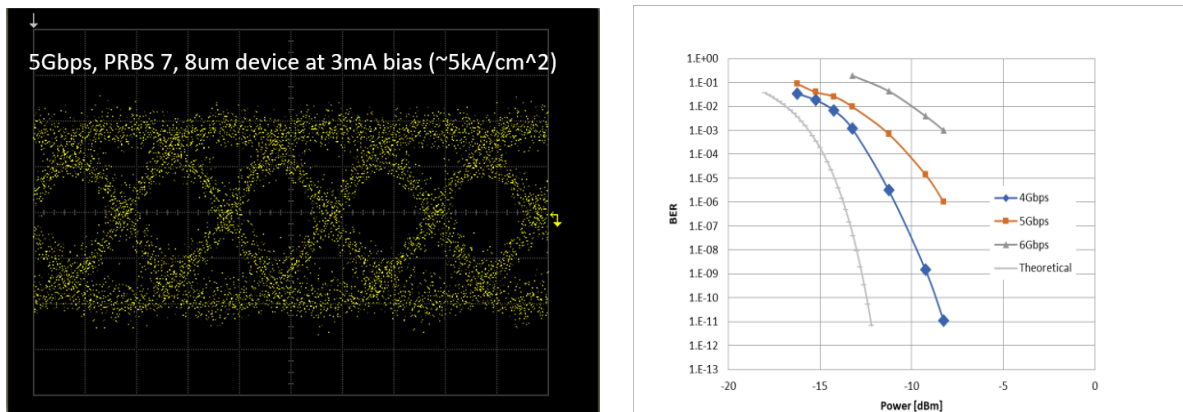


Fig. 4: 25C eyes and BER of 8μm diameter microLED at various speeds and about 5kA/cm² drive current.

Finally, individually addressed arrays were tested through an imaging fiber. The fiber, very similar to that used in earlier work of reference 2 is simply butt-coupled to the array and to the detectors on the other side. Thus 8 individual links could be modulated simultaneously. Fig. 5 shows the BER for the 8 emitters at 1.25Gb/s, with an aggregate bandwidth of 10Gb/s. The total speed of this link was limited by the small number of emitters and the relatively slow speed. The imaging fiber diameter was about 400um and could have supported a much larger array of emitters and of course modulation speed can be increased to 5Gb/s. We expect such a scheme to easily support 256 emitters at 4Gb/s each and thus readily achieve 1Tb/s per fiber.

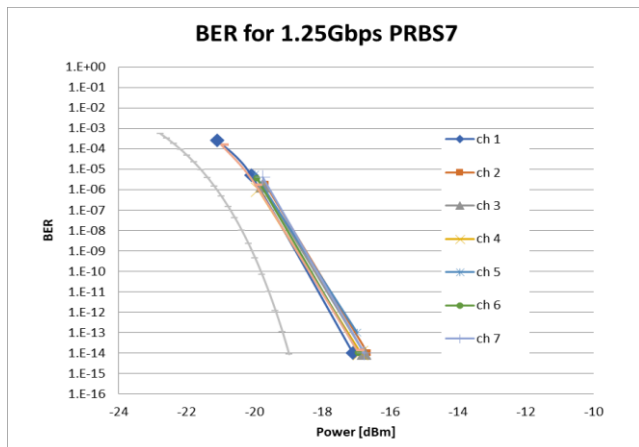
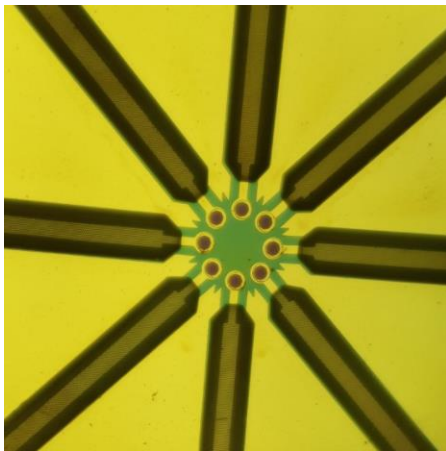


Fig. 5: 8 element individually addressed array with BER through an imaging fiber at 1.25Gb/s and aggregate fiber bandwidth of 10Gb/s

5. SUMMARY

We describe the fundamental trade-off between brightness and speed in microLEDs and present characterization data on high-speed versus standard devices, and derive radiative and non-radiative lifetimes. For the first time, we show that microLEDs can be very fast, even at low current densities. Finally we show link performance of high speed microLEDs both in low current density and high current density modes. We expect these devices in various configurations to be very useful for the electronics industry, opening up the interconnect bandwidth that is choking large ASICs and interconnect rich applications such as high performance parallel computing and machine-learning applications.

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