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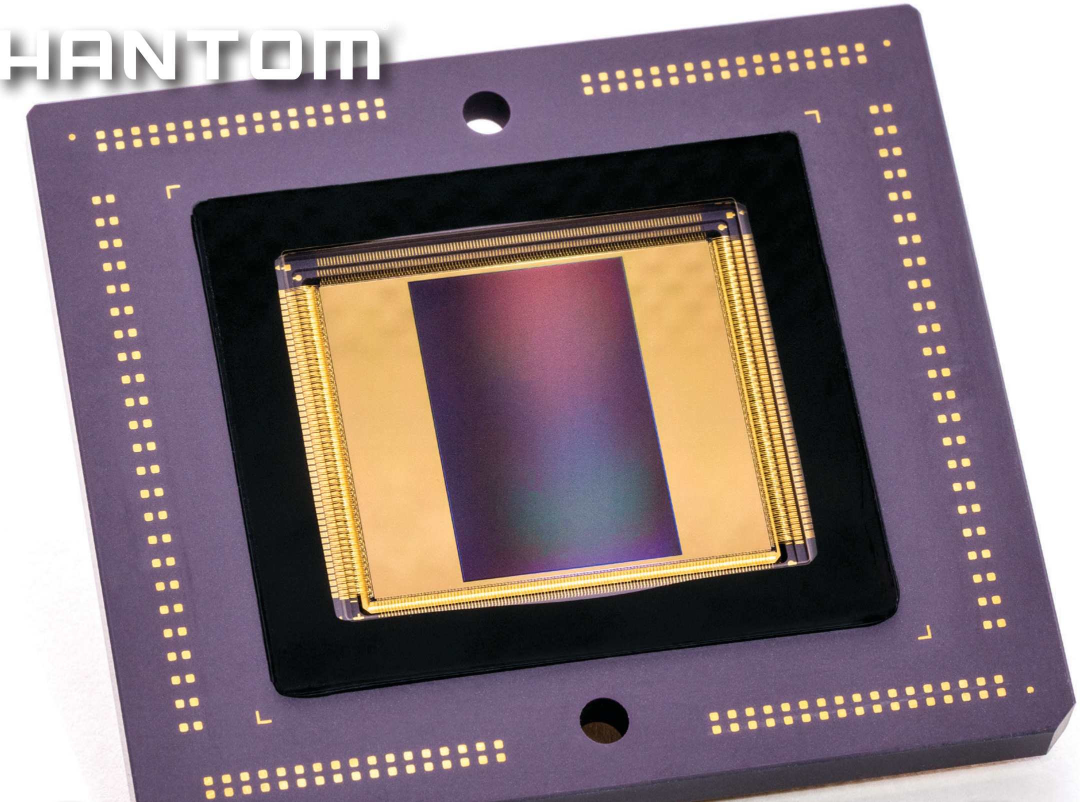


# Back Side Illumination Gets Fast

## New Sensor Drives High-Speed Imaging Improvements

With speeds of over 1 million frames per second, high-speed imaging is an invaluable research tool capable of capturing the most fleeting events in scientific and engineering applications. Yet achieving this speed comes with strings attached. Most high-speed cameras are designed to achieve a maximum gigapixel/second (Gpx/sec) throughput, offered in a trade-off of frame rate to resolution. For example, a 25 Gpx/sec camera reaches 25,700 frames per second (fps) at a resolution of 1280 x 800 pixels and can achieve a higher frame rate of 28,500 at a smaller resolution of 1280 x 720. Both combinations have almost the same throughput. Very high frame rates such as 1 million fps are accompanied by very small resolutions, making it more challenging to see the subject matter.

As frame rates increase, the exposure time a pixel has to light decreases. At 25,700 fps, each frame has a maximum exposure of 39 microseconds (μs), and at 1 million fps, the maximum exposure time is only 733 nanoseconds (ns). The short exposure times require high levels of illumination to compensate for the short time the pixel receives light. In fact, many high-speed applications are light starved — meaning that, given the very short exposure times at high frame rates, the available illumination won't deliver enough light to the camera's imaging sensor to produce an ideal image and may even be impractical in certain applications.

DEVELOPED BY:

PHANTOM®

VISION RESEARCH

AMETEK®
MATERIALS ANALYSIS DIVISION

*When it's too fast to see, and too important not to.®*

High-speed camera operators have become adept at balancing their need for speed and resolution with their need for adequate illumination. They are able to capture spectacular images that advance the frontiers of scientific understanding and engineering analysis, but the trade-offs become more difficult to manage as users push the boundaries of high-speed imaging.

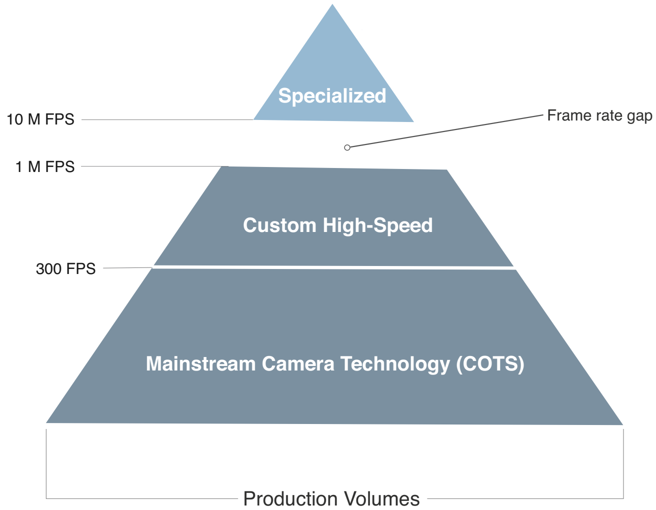
Recently, we made a technical breakthrough that eases the speed-resolution-sensitivity constraint. We've developed a new high-speed image sensor that employs back side illumination (BSI) to increase the pixel surface area that can capture photons. Because it's more effective at capturing light, the BSI sensor is better suited for applications requiring high frame rates. In this camera, throughput — max frame rate times max frame resolution — increased by a factor of three times compared to previous generations of high-speed CMOS imaging sensors. The new sensor debuted March 2021 in our new Phantom TMX cameras, the fastest of which can shoot 76,000 fps at a full resolution of 1280 x 800 pixels *(see sidebar)*.

In this technical article, we'll explain how BSI works as well as the challenges and benefits of using BSI sensors for high-speed imaging. We'll also delve into other sensor architecture improvements that contributed to the new sensor's best-in-class speed and performance.


*The Phantom TMX 7510*

## BRINGING BSI TO HIGH-SPEED APPLICATIONS

Until now, the CMOS sensors used in high-speed cameras have been based on front side illuminated (FSI) architectures, in which the sensor's metal circuitry sitting above the pixels' photodiodes is facing the light source. This metal circuitry prevents some incident light from reaching the pixels, which in turn affects the fill factor and reduces the sensor's sensitivity. BSI sensors are designed with a thick carrier wafer attached to the top of the metal stack. This arrangement allows the bulk silicon to be thinned and flipped to expose the diodes facing the light source and the metal surface behind them. There are two significant advantages to BSI sensors in high-speed: improved fill factor, by providing a direct route for light to reach the light-receiving surface *(see Figure 1)*, and improved processing speed, by adding more metal to the sensor's metal surface.




*Back side illuminated (BSI) technology applied to high-speed imaging starts to close the frame rate performance gap between custom high-speed capability and specialized imaging capability.*

**Improved fill factor:** This effectiveness at capturing incident light is expressed in terms of the sensor's fill factor — or the percentage of the pixel surface area that is able to capture photons. With its metal circuitry blocking or reflecting some of the light, a typical FSI sensor used in high-speed imaging will have a fill factor between 50 and 60%, partially compensated for by a microlens in typical current FSI sensors. By moving the circuitry out of the way, our new BSI sensor has a fill factor of close to 100%.

### Introducing Phantom TMX Ultrahigh-Speed Cameras

Our new TMX ultrahigh-speed cameras are the first to use the new BSI sensor. The TMX 7510, the fastest member of the series, offers the fastest frame rates at the largest resolutions available today:

- With 75 Gpx/sec of throughput, the TMX 7510 can achieve speeds up to 76,000 fps at a full resolution of 1280 x 800 and reach over 300,000 fps at 1280 x 192.
- The TMX achieves high speeds at double the resolution height with 2 x 2 pixel binning — for example, 308,000 fps at 640 x 384 binned.
- TMX reaches 1.75 million fps at resolutions of 1280 x 32 or 640 x 64 binned with Export Controlled FAST option. Minimum exposure time of 95 ns is also included with the FAST option.

Aside from its game-changing sensor, the TMX has been designed with data management in mind, offering up to 512 GB of memory and up to 8 TB of CineMag secure storage. For fast data transfer, 10Gb Ethernet is standard.

Finally, the TMX has a range of control options. These include programmable I/O for flexible signal control, on-camera controls and video monitoring for computer-free operation and a wide range of signal ports to adapt to different application needs.

Export Controlled FAST option is required for performance of 1 million fps or higher and exposure time under 1 µs.

*Learn more about the TMX family of ultrahigh-speed cameras at **www.phantomhighspeed.com/TMX***

**Increased processing speed:** The basic speed of the pixel array is limited by resistor-capacitor (RC) time constants, and adding metal reduces the resistance and increases the speed. In FSI sensors, the amount of metal on the sensor front is limited to allow light to reach the photodiodes. This constraint leads to overhead in the processing speed. As frame rates increase and resolutions decrease, the camera cannot provide maximum Gpx/sec throughput because of losses to overhead. BSI sensors do not have this constraint and can have significantly increased metal circuitry, substantially reducing or even eliminating overhead.

# CMOS IMAGE SENSOR ARCHITECTURES

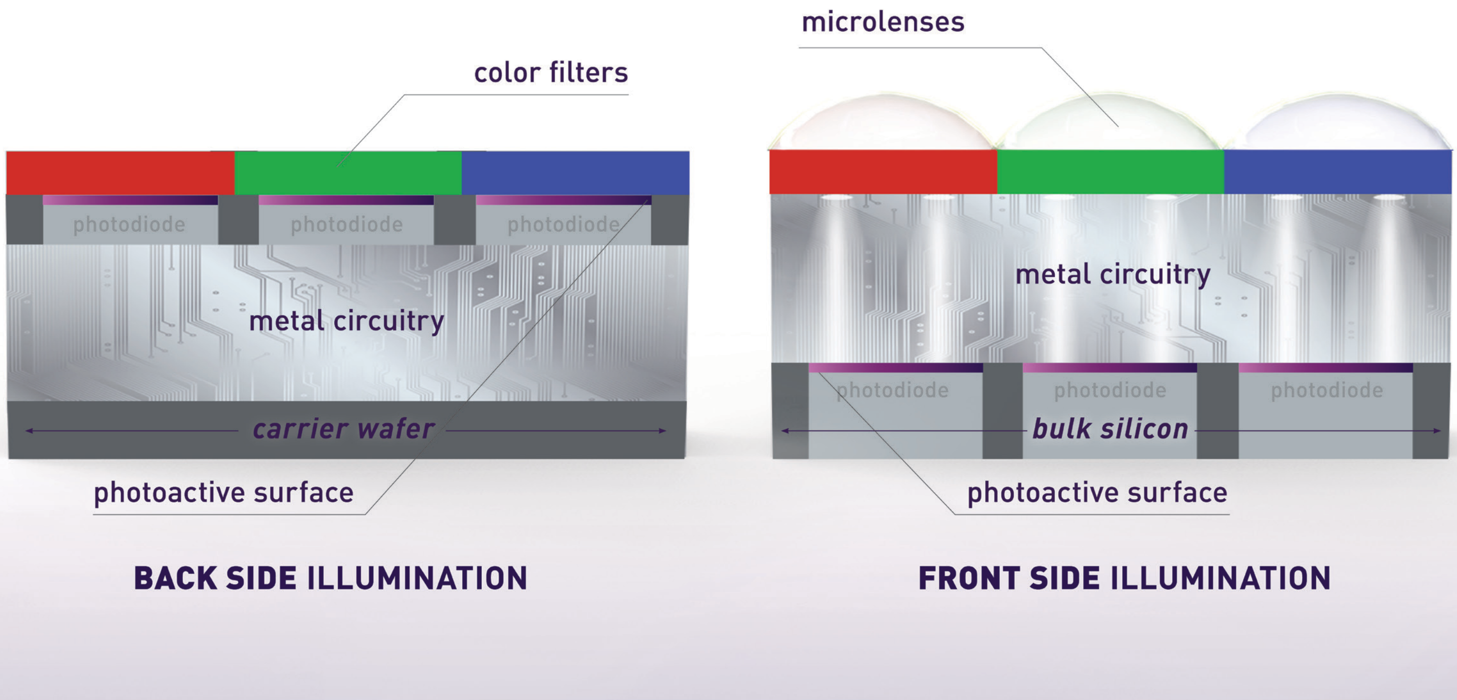



*Figure 1: BSI sensors improve fill factor by providing a direct route for light to reach the light-receiving surface.*

This capability allows a BSI sensor to maintain its maximum Gpx/sec throughput even at very high frame rate/low resolution combinations.

BSI sensors have been available for more than 10 years in a variety of cellphone and standard digital cameras. They've offered proven advantages when it comes to improving low light performance and dynamic range of these consumer-focused cameras. Why did it take so long to bring these sensors to high-speed imaging? In a word, size.

The sensors and pixels used in high-speed cameras are much larger than standard cameras to minimize our speed-resolution-sensitivity trade-offs. For instance, while a cellphone camera may have a pixel that measures less than 2 µm per side, our image sensor pixels are typically more than 6 µm and as much as 28 µm per side.

The manufacturing process for BSI sensors is inherently more difficult than comparable FSI sensors and requires additional manufacturing steps. Among them is a wafer *backthinning* step to remove the bulk silicon, bringing the photodiodes closer to the light source. There are also additional processing steps on the back side of the wafer to anneal the surface and provide electrical contacts to the front side. The size of high-speed image sensors only exacerbates manufacturing difficulties. The realities of semiconductor economics also made it difficult to transfer the technology from the high production volumes of standard cameras to the comparatively low volumes of high-speed imaging sensors. It took time to perfect the manufacturing process and achieve practical yields.

The BSI image sensor has been worth the wait. It sets new standards for:

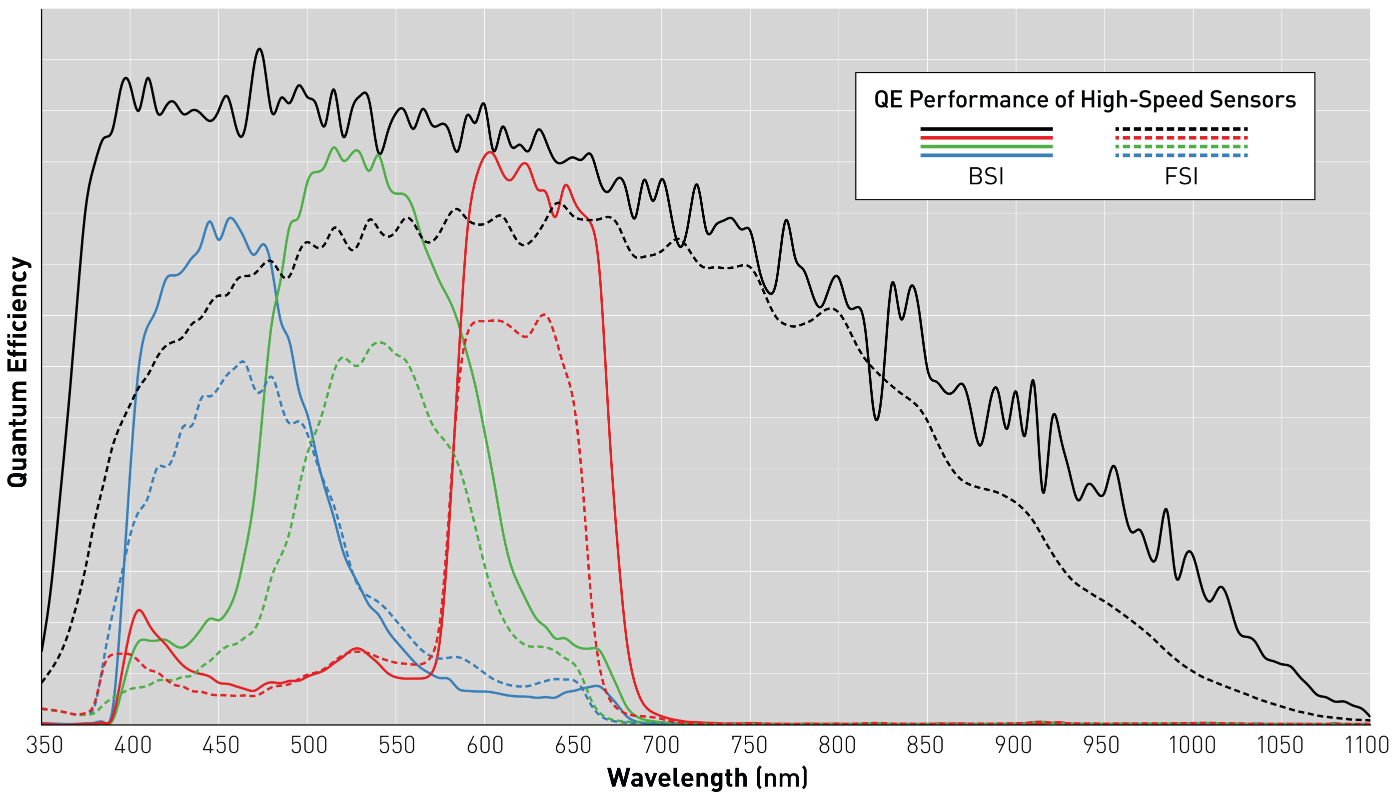
- **Speed.** The first camera using the sensor captures images at 76,000 fps at full 1-megapixel (1280 x 800) resolution, and it can reach speeds more than an order of magnitude faster at reduced resolutions and with binning. For example, the camera tops out at 1.75 million fps with a resolution of 1280 x 32 and 640 x 64-pixel binned. Historically, the resolutions associated with frame rates above 1 million fps were too low for nearly all scientific uses, but 1280 x 32 represents a truly usable resolution in a wide range of applications.

- **Exposure times.** The new sensor supports minimum exposure times as fast as 95 ns with Export Controlled FAST option, making it the fastest in its class by far. The fast exposure times make it possible to capture ever-faster events without motion blur, which can be a limiting factor in obtaining high-quality images in applications as wide ranging as cytometry and combustion analysis.
- **Pixel size.** To work in light-starved conditions, high-speed cameras have historically used very large pixel sizes as a means to catch as many photons as possible. Our existing FSI ultrahigh-speed sensor, for example, has a pixel size of 28 μm per side for an area of 784 μm$^2$. The new BSI high-speed image sensor has an 18.5 μm per side pixel, but its proficiency at capturing light makes it about as sensitive at three times the speed as earlier FSI sensors with 28 μm pixels. Smaller pixels also improve sampling frequency (Nyquist), allowing the sensor to resolve higher lp/mm spatial frequencies before aliasing.
This capability enhances the imaging system's performance in flow cytometry, particle image velocimetry (PIV), digital image correlation (DIC) and other high-speed applications limited by the resolving power of the sensor.

## BEYOND BSI

The performance breakthroughs associated with the new image sensor design mainly rest on its BSI architecture, but there's more to the design. The new sensor also has a number of design features that boost performance beyond what BSI could accomplish alone — particularly related to the ability to read out the massive amounts of imaging data at high speeds and improve throughput.

### QE COMPARISON OF BSI AND FSI SENSORS
MONOCHROME AND COLOR




*Compared with FSI sensors, BSI sensors achieve a higher quantum efficiency (QE) throughout the visible light spectrum.*

**Solving analog-to-digital conversion challenges.** Embedding analog-to-digital converters (ADC) on CMOS image sensors is standard practice, but the BSI sensor's speed required a massive increase in the amount of ADC. While modern CMOS image sensors typically have between 1,000 and 10,000 embedded ADC, the new BSI high-speed sensor has 40,000 ADC, each converting every 523 ns and generating a large amount of data to off-load from the sensor. To accomplish this task, it incorporates 160 high-speed serial outputs operating at greater than 5 Gbps. This technology is common on CPUs and FPGAs but new on a high-speed imaging sensor.

The density of ADC on the new sensor did create power management and electrical crosstalk challenges, which were solved with the help of our design and integrated production partner, Forza Silicon. While simulations are often used in predicting sensor performance, this sensor required the simulation to calculate for weeks to provide a prediction. Forza has significant experience in simplifying simulations and analyzing actual versus predicted results for fast design modifications. In the case of the BSI sensor, testing of early designs revealed a higher level of ADC crosstalk in both normal imaging and binning modes than our simulation tools had predicted, causing noticeable artifacts in the images. Forza engineers discovered that the crosstalk exhibited predictable patterns and developed modeling techniques that helped us eliminate the crosstalk altogether, which in turn mitigated imaging artifacts.

**Binning for maximum throughput.** The sensor supports 2 x 2 binning to maximize throughput at faster speeds. Though not common in high-speed sensors, we've implemented binning in two previous cameras. It helps mitigate limitations of the sensor's column ADC architecture, enabling faster speeds than simply decreasing the y-dimension. This approach is subtly different than binning as applied in CCD cameras, where it's used to primarily boost sensitivity. In this case, we're using it to boost speed.

## BSI DIFFERENCE

BSI is not a new technology, and it has been used with great success in standard and cellphone cameras. By adapting it to high-speed imaging, we've been able to create a sensor that pushes the boundaries on speed in light-starved conditions.

***To learn more, visit www.phantomhighspeed.com/TMX***

### ABOUT VISION RESEARCH

Vision Research, a business unit of the Materials Analysis Division of AMETEK Inc., designs and manufactures high-speed cameras. The Phantom camera brand is known for unparalleled light sensitivity, image resolution, acquisition speed and image quality — necessities for analyzing high-speed events.

Vision Research offers the broadest range of high-speed cameras to meet the needs of a variety of industries. Used for research and development, the VEO series is popular in academia due to its simple features and budget-friendly models. The ultrahigh-speed series delivers clear images and exact data at the fastest speeds possible. Vision Research has also recently developed a new line of streaming cameras for the machine vision industry that accommodates real-time analysis and long record times.

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*Certain Phantom cameras are held to export licensing standards. Please visit www.**phantom**highspeed.com/export for more information.*