An Objective Look at FSI and BSI

An Aptina™ Technology White Paper

Introduction

Image sensor pixel technology has advanced tremendously in the past 30 years as a result of innovations in light gathering techniques and semiconductor process technologies. A variety of different technologies have emerged to meet the challenging requirements of consumer products. To see how far the technology has come, one can look to the first camcorder image sensors that used 25 micron pixels with well capacities in excess of one million electrons. Today, image sensors found in cell phone cameras utilize pixel sizes as small as 1.4 micron with 5000 electron well capacities, and the market is beginning to push toward 1.1 micron pixels. Even as the market continues to demand smaller pixels, image sensor manufacturers are expected to provide improved imaging performance despite challenges imposed by the use of standard logic or memory integrated circuit (IC) manufacturing technology to produce the sensor products.

Certainly, the ultimate goal is to build image sensors that capture and completely transform the incident patterns of light into signals that accurately and efficiently record intensity, as well as spatial and color information. Standard IC fabrication processes and imaging-specific process enhancements have led to the development of image sensors utilizing frontside illumination (FSI). With FSI, light falls on the front side of the IC, and passes through readout circuitry and interconnects before it is collected in the photodetector. This process is not unlike the human retina where the light passes through a layer of interconnected nerve cells before being detected by the eye's rods and cones.

However, at some point, the physical limitations caused by unchanging light wavelengths and shrinking pixels will require a shift in this paradigm. One path forward is to effectively remove the readout circuitry and interconnects from the light path by illuminating the sensor from the backside, or backside illumination (BSI). The potential benefits of BSI are intriguing, yet manufacturing challenges suggest that it might be advantageous to postpone this transition as long as FSI image sensors can be built to meet the performance requirements of the market.

In this paper FSI, BSI, and the idea of the "perfect pixel" will be explored in detail to objectively evaluate the technologies addressing the shrinking pixel challenge.

The Perfect Pixel

Both FSI and BSI technology strive to create the perfect pixel. The "perfect pixel" accepts all light, classifies it by color content, preserves its spatial information, and produces an output representative of its intensity – all in a lossless manner. Yet, like all things perfect, such a pixel cannot be achieved. While this ideal cannot be realized, exploring the concept forces us to consider all mechanisms that cause photons to be lost and work to minimize the loss.

The idea of the perfect pixel begins with the notion that no light is lost while passing through the structures above the silicon. Additionally, the light color is classified by directing all the light entering the pixel to pass through a color filter that separates the light into the trichromatic (i.e., red, green, blue) coordinates used to recover color information. The color filter should perfectly transmit the desired colored photons and block the other colors.

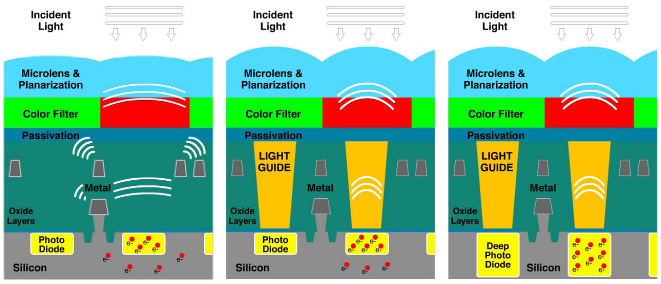
To preserve spatial information, the light leaving the color filter must be directed into a photodetector. This photodetector should have a well-defined volume capable of absorbing photons of all wavelengths, be spatially isolated from neighboring photodetectors, and capture all light entering it. Next, without the loss of any light, this perfect photodetector must convert the light into an electrical signal (i.e., collect all photo-generated carriers).

The resulting perfect pixel would have 100% quantum efficiency (QE) and zero optical and electrical crosstalk.

FSI Technology: How it Works

Image sensors have traditionally been designed for fabrication flows that result in an end device where light enters from the front side, between the metal control lines, and is focused down onto the photodetector. A simplified diagram of standard FSI is shown in the leftmost diagram of Figure 1. Historically, for larger pixels, FSI worked well because the ratio of pixel stack height to pixel area was such that the aperture of the pixel was large.

Figure 1: Simplified diagram of light propagation in a pixel and electron generation from the light



Standard FSI

FSI with Lightguide

FSI with Lightguide & Deep Photo Diode

Ever-shrinking pixels have required a series of pixel technology innovations to accommodate material and manufacturing limitations related to frontside illumination.

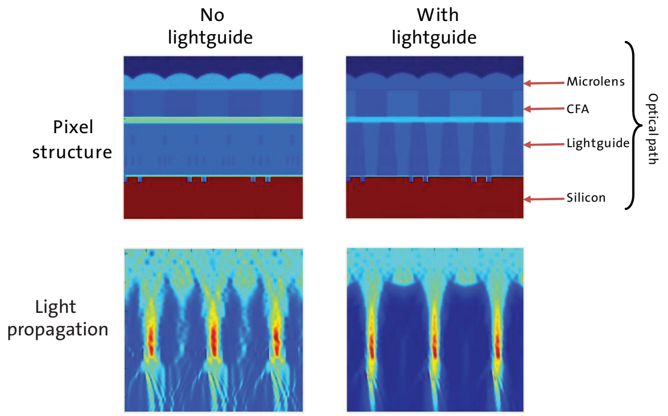
One FSI innovation path was to introduce a series of process enhancements to optimize the optical path of the FSI pixel. These enhancements have included microlenses with optimized shape, optimized color filters, recessed pixel arrays, lightguides, and anti-reflective coatings.

The light entering the FSI pixel is initially focused by an anti-reflective coated microlens that acts as an aperture. Microlens engineering is required to accommodate both the quality of lenses and aggressive chief ray angles (CRA's) used in mobile handsets. Light passes through the microlens and is concentrated on a color filter with optical density and thickness engineered to optimize low-light response and signal-to-noise ratio (SNR) and to ensure the clean separation into trichromatic components. The microlens curvature and thickness are determined specifically so that the light transmitted by the color filter has a high acceptance into the lightguide.

The lightguide is engineered to gather the light from the microlens and confine it to a narrow beam as it passes through the stack of interconnect metals and isolation. Adding the lightguide effectively shortens optical stack height; meaning that the point where light converges is raised from the silicon surface to the top of the lightguide as shown in the center diagram of Figure 1. This results in a collimated light beam being directed into the photodiode volume as shown in Figure 2.

The lightguide must collect light entering anywhere within the cone of light and range of chief ray angles (CRAs) provided by the aperture – careful lightguide materiel design is key to accomplishing this. Moving to a more advanced semiconductor manufacturing process with smaller minimum feature size (e.g., from 90 to 65 nanometer), and changing the metal from aluminum to copper provide the benefit of narrower metal widths, which enable the introduction of a wider lightguide that will accept more light. In conjunction with these advances, the pixel array can be recessed which reduces the stack height above the pixel array to the thickness of just two layers of metal.

Figure 2: An FSI pixel array with lightguide reduces light scattering so that light power is concentrated in the photodiode volume



Large amount of light scattering results in reduced QE and increased crosstalk

Light scattering is greatly reduced, resulting in higher QE and lower crosstalk

As a final addition to these process and structure enhancements, adjustments in layer thicknesses and material substitutions help to minimize reflections at the surface of the microlens and in the layers immediately above the silicon surface.

Once the lightguide has delivered the photons to the silicon surface, the photodiode takes over. Given the absorption properties of light in silicon, the photodiode ideally needs to have a volume that extends to a depth of several microns. A photodetector can be engineered to extend the depletion depth into the silicon wafer to achieve the dual goals of maximizing the collection of photons and of preserving spatial resolution. This is shown in the rightmost diagram of Figure 1. The key here is to maximize the isolation between adjacent photodiodes and to form a deep junction to remove any photocharge generated by long wavelength photons that are not absorbed in the photodiode.

BSI Technology: How It Works

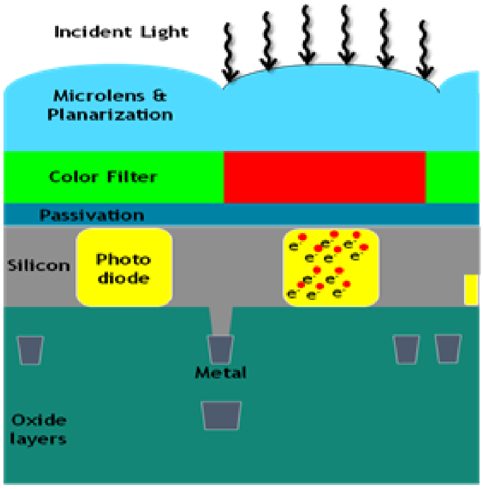
A pixel built for backside illumination eliminates the need to pass light through the layers of metal interconnections, as shown in Figure 3. However, there are still constraints imposed on the optical path that need to be engineered. Fortunately, much of the learning and many of the advances that have enabled the continued improvement of FSI pixels can be directly applied to BSI – providing an excellent foundation to take BSI to higher levels of performance.

BSI technology starts with the incident light focusing into the optical volume of the photodiode. There is still a need for color separation, which necessitates patterning color filters and microlenses on top of the array – which has now been inverted. The optical requirements are the same as for FSI, except that with the microlenses now located closer to the photodiode, the deposition of a thicker microlens materiel layer is required to achieve the shorter focal length.

Unlike FSI, which has a natural aperture created by the interconnect layers; the need to minimize crosstalk in BSI necessitates the introduction of an aperture through the deposit of a metal grid above the photodiode.

Because the BSI wafer has been inverted, the incident light in BSI first strikes the silicon volume away from the photodiode where light may be lost from crosstalk due to diffusion to adjoining pixels or lost due to diffusion and recombination at the back interface. Blue light in particular is susceptible to this phenomenon, resulting in decreased blue QE and increased crosstalk. These issues can be addressed with the introduction of a deeper photodiode to capture the blue light and through advanced backside processing.

Figure 3: Simplified diagram of a backside illuminated (BSI) pixel



FSI and BSI: Advantages and Disadvantages

FSI Advantages

A key advantage of FSI technology is its maturity and the benefits that come along with that: proven high volume mass production, reliability, and yield. These benefits combine with a high performance level to create a unique performance/cost value proposition that is continuing to drive widespread use of the technology.

More advanced FSI pixels that utilize optimally engineered lightguides bring the benefit of lower crosstalk that results from the lightguide channeling the light into the correct pixel. The lightguide also has the benefit of enabling higher acceptance angles for the incoming light, which allows camera lenses with higher chief ray angles, and provides increased flexibility in camera module design (i.e., lower height modules).

FSI has the advantage of lower cost with equivalent performance when compared to BSI. This cost advantage comes from requiring fewer processing steps, and from achieving the higher yields associated with a more mature manufacturing process. The equivalent imaging performance (for 1.4 micron pixels) is a result of FSI's lower crosstalk balanced against BSI's higher quantum efficiency (QE) to generate output images with similar signal to noise ratios (SNR).

The latest advances in FSI technology optimally channel photons through the color filters and interconnect layers, to be efficiently captured in the deep photodiode. These advances achieve high performance for commercial image sensors with 1.4 micron pixels without needing to make the leap from FSI to BSI (see Figure 4 for an example image captured in low light conditions).

Figure 4: Image from 8 Megapixel 1.4 micron pixel FSI sensor at 30 lux illumination

Further, these advances have resulted in state-of-the-art 1.4 micron pixels that can typically achieve a QE in the 50-60 percent range with crosstalk in the 5-15 percent range. As we will see later, this QE approaches that of BSI, but with FSI's typically lower crosstalk, the net overall image quality is comparable for 1.4 micron pixels.

FSI Disadvantages

FSI's challenge, from the beginning, has been getting the incoming light through the metal layers of the silicon to the photodiode. To do so necessitates the creation of a small aperture within the pixel. In order to widen this aperture to collect more light, pixels are designed with shared components to help minimize the circuitry above the photodiode. While this improves QE, the sharing introduces asymmetries that then must be compensated for with engineering solutions (note: this asymmetry is independent of the lightguide).

Additionally, these apertures introduce diffraction effects and the higher pixel stack height makes it more challenging to prevent crosstalk with the pixel's high aspect ratio. While lightguides mitigate these undesired effects, even the best lightguide is not completely lossless.

Scaling from 1.4 to 1.1 micron pixels significantly increases the challenge of engineering a lightguide due to physical limitations. There is a point, as pixels continue to shrink, where diffraction effects will prevent satisfactory optical acceptance even with enhancements such as lightguides. Further, FSI has the disadvantage of not being able to use all of the available metal interconnect layers for on-chip processing, which may become more of a limitation with 1.1 micron pixels.

FSI Summary

FSI is the dominant technology used in image sensors today with billions of frontside illuminated sensors having been sold. The performance/cost value proposition of the technology has enabled it to drive adoption of cameras in cell phones, notebook computers, digital video and still cameras and numerous other applications.

Even as BSI is expected to be required for future applications requiring 1.1 micron sensors, FSI is expected to fuel a new generation of products as well. FSI is particularly well suited for applications that require “bigger” pixels – where low light and overall imaging performance is more critical than just moving to higher resolution. Video-driven applications and, in particular, high-definition (HD) video, put a premium on getting better performance at HD resolutions. For high-quality HD video, which is becoming increasingly important, 1.4 micron and even 1.75 micron or larger pixels using FSI technology are expected to have a long life.

BSI Advantages

The principal advantage of BSI is its ability to separate the optical elements from the electrical elements, allowing a photodiode with its electrical components on one side, and the optical path on the other. This means that the optical path can be optimized independent of the electrical and vice-versa. Also, this removes the need to create an aperture, either from metal or from a lightguide, eliminating a loss mechanism for the incident light. The net result is that BSI can ultimately achieve a higher QE.

Another major advantage of BSI over traditional FSI image sensors is the pixel’s shorter optical stack. Though it should be noted this advantage is less pronounced when compared to an FSI structure with a lightguide. This is because the effective optical stack height is decreased when the light is gathered at the top of the interconnect stack and confined and channeled by the lightguide down to the photodetector surface.

For 1.4 micron BSI pixels, QE is typically in the 50-60 percent range with crosstalk in the 15-20 percent range. The combination of BSI’s high QE and somewhat degraded crosstalk at 1.4 micron results in a net overall image quality that is comparable to FSI for 1.4 micron pixels. It should be noted that 1.4 micron BSI has not yet ramped to high-volume production in the market, but as with pixel technology in general, the performance would be expected to improve over time. Today, 1.1 micron BSI pixels are still in the early stages of development, but when they are production-ready, they would be expected to have a QE approaching 50-60 percent with crosstalk in the 10-30 percent range. These 1.1 micron BSI pixels should be outperforming 1.1 micron FSI pixels at that point due to the fabrication challenges in shrinking FSI pixels to 1.1 micron.

BSI Disadvantages

Crosstalk challenges arise with BSI due to the device structure. As a result of this crosstalk some photons are collected in the wrong pixel which degrades the color correction matrix, leading to decreased SNR.

Extra processing is needed with BSI in fabricating the wafers, which introduces additional costs and tolerances. Examples include processing to allow mounting on a carrier wafer and thinning, processing to provide alignment marks for backside processing, and processing to passivate the backside interface. In addition, there is the CFA and microlens processing that would have been done on the front side, but now must be done on the backside where alignment is more difficult due to wafer warping and the challenge of aligning structures on the opposite side of the material.

The higher costs associated with BSI are causing some image sensor manufacturers to initially target high-end, less cost sensitive camera applications. An example is Sony whose BSI sensors primarily target high-end digital video cameras and digital still cameras. One image sensor vendor executive, Bruce Weyer, VP Marketing at OmniVision, had this to say about the higher costs associated with BSI technology, “It typically would carry a higher average selling price. The technology also has more advanced process technology involved with it, so it also carries a little bit higher cost basis as well.”[1]

Another disadvantage is that the back surface has to be passivated, creating a less favorable surface to work with than the front side surface, resulting in limited process options. Additionally, having the carrier wafer bond and metallization already on the front side of the wafer also limits the processing options. As a result, passivation layers need to be deposited on the back side surface instead of grown, and the defects in the passivation layers will impact

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[1] *http://seekingalpha.com/article/191143-omnivision-technologies-inc-f3q10-qtr-end-01-31-10-earnings-call-transcript?page=8*

the defects on the back surface, resulting in higher dark current and higher probability of hot pixel defects.

Finally, creating a BSI image sensor requires significant new process development and time for this new technology to mature and move up the yield curve. Yet, with most major image sensor vendors investing in the development of BSI processes – it is just a matter of time before these hurdles are overcome. This immaturity of BSI technology was characterized by OmniVision CFO Anson Chan in this manner, "this is clearly in early stage in the life cycle of this kind of product technology and we do have room for (margin) expansion to the extent that we can resolve these yield issues and what not as we start the volume ramp."[2]

BSI Summary

BSI is early in its development and naturally the disadvantages will be minimized over time. As BSI performance continues to improve and the technology matures its use can be expected to become more widespread.

Today, BSI is primarily finding use in high-end consumer cameras where paying a premium for the sensor is less of a concern for the manufacturer. For example, camcorders with BSI sensors sell in the $700 to $1200 price range and several BSI-based digital still cameras sell in the $350-500 price range. Given BSI's higher cost, high-performance cost-effective FSI sensors will challenge the ability of BSI to migrate to lower price points in these larger pixel applications.

A tipping point for BSI will be the 1.1 micron pixel node where FSI will likely be unable to achieve the market-required performance – necessitating a transition to BSI for applications that require this smaller pixel.

Conclusion

The perfect pixel that collects every desired photon of light and perfectly converts it into an electrical signal is the holy grail of image sensors. Though it will never be attained, the quest for the perfect pixel drives the expenditure of hundreds of millions of R&D dollars industry-wide by image sensor companies every year. The beneficiary of most of that pixel R&D to date has been FSI technology. FSI has enabled pixels to cost effectively shrink to 1.4 microns while continuing to advance in performance for a given pixel size each year.

Aptina has been the leader in introducing new technologies such as lightguides and deep photodiodes, and in investing to solve the hard engineering problems to bring these technologies to the market with industry leading performance and reliability. FSI will continue to improve and play a leading role in enabling applications such as HD video; it will continue to have a long life. In recent years, as the future limitations of FSI technology became apparent, the industry has moved some of its pixel R&D investment to BSI technology. While already finding applications in more expensive cameras today, BSI technology is being advanced such that the day will soon come where it finds widespread use in mainstream high-volume applications.

About Aptina

Aptina is a global provider of CMOS imaging solutions with a growing portfolio of products that can be found in all leading mobile phone and notebook computer brands as well as a wide range of products for digital and video cameras, surveillance, medical, automotive and industrial applications, video conferencing, barcode scanners, toys, and gaming. Aptina enables Imaging Everywhere™ and continually drives innovation in the market as seen with the introduction of the first 14MP CMOS image sensor for point-and-shoot and hybrid cameras (MT9F001), and the industry's first 5MP SOC with ¼" format (MT9P111). Privately held Aptina's investors include Riverwood Capital, TPG Capital and Micron Technology. For additional information on Aptina and news on technology webcasts visit *www.aptina.com*. Subscribe to the latest news from Aptina by copying the *Aptina RSS feed* into your favorite RSS reader.

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[2] *http://seekingalpha.com/article/191143-omnivision-technologies-inc-f3q10-qtr-end-01-31-10-earnings-call-transcript?page=9*