The Future of Endoscopy is CMOS

It's Time to Transition from CCD

White Paper

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Introduction

Endoscopy enables minimally invasive diagnosis and treatment of a variety of conditions, from cancers to heart disease. Endoscopes for natural orifice transluminal endoscopic surgery (NOTES) or surgery via small incisions provide a safer and faster alternative to conventional surgery. Many underlying socio-economic, legal, and technical trends are driving the rapid global transition to endoscopy.

Although endoscopy has existed for decades, legacy technology based on charge-coupled device (CCD) image sensors has reached its limits. Also, the high cost of CCD image sensors and the overall system complexity make their use impractical in an exponentially growing single-use endoscopy market.

Due to advances in components, materials, and surgical tools, endoscopy is becoming an ever more versatile and omnipresent method for diagnostic and therapeutic procedures. Two trends are converging to change the landscape for medical device manufacturers.

First, a greater variety of procedures involve endoscopy. The outer diameter of the endoscope must be small enough to insert and manipulate within the human anatomy. For imaging of the gastrointestinal tract, the endoscope enters the body through relatively large opening and older endoscopes with larger diameters can be used for these procedures.

In contrast, procedures in smaller parts of the anatomy, including the brain, eyes, ear/nose/throat (ENT), spine, heart, urinary tract, and more, require entry through smaller openings (figure 1). For these procedures, the diameter of the endoscope is less than 3 mm, thus precluding the use of chip-on-tip CCD.

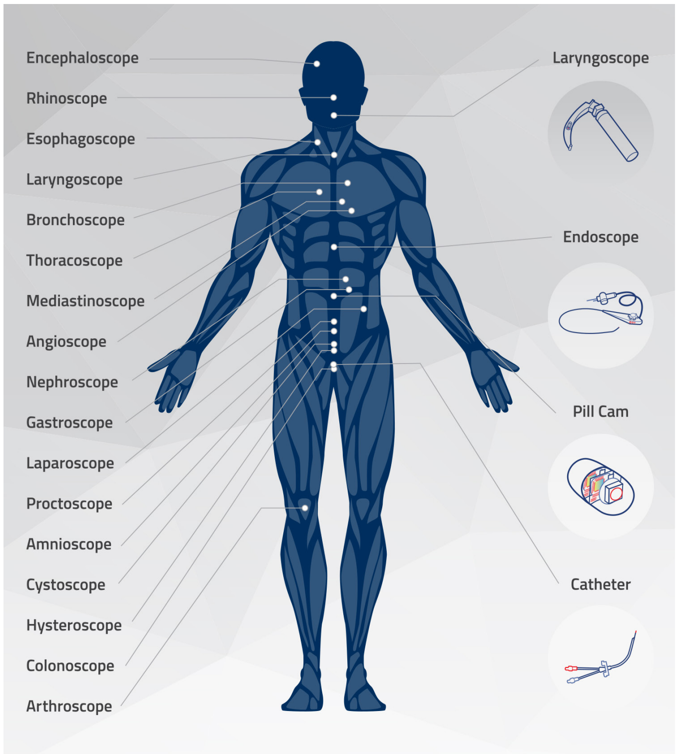

Figure 1—Different types of endoscopes target specific areas of the human body.

The second trend is to avoid cross-contamination. Consequently, there is an increased demand for single-use endoscopes. In addition, as endoscopy expands from hospital to clinic settings, there is no longer space for the large, expensive cleaning equipment required for reusable endoscopes. Portable, single-use devices give small clinics around the world access to endoscopy.

These trends in endoscopic procedures and healthcare settings call for small, cost-effective, high-resolution endoscopes. Because CCD-based image sensors cannot meet the requirements, they are being phased out. Fortunately, more advanced image sensors are available to replace them.

Image sensors that use complementary metal oxide semiconductor (CMOS) technology offer the latest imaging solution. This paper challenges common perceptions about CCD-based endoscope imaging technology and explains how CMOS-based image sensors will enable further advances in this life-saving diagnostic and therapeutic tool.

CCD: Limitations for Endoscope Imaging

For decades, cameras based on CCD image sensors have been the gold standard for endoscopic imaging. Many endoscope manufacturers and medical personnel believe that CCD technology offers the highest image quality.

Ten years ago, that perception was perhaps true. However, that is no longer the case, as the demands of more complicated endoscopic procedures push beyond the limits of CCD image sensors. The primary issues are limitations on pixel size, power consumption, and data rate.

The minimum pixel size for standard progressive CCD architectures is 3 μm. It is difficult to shrink the pixel size further without reducing the photodiode size, which would worsen image quality. Interline architectures, which allow transfer lines to take up less space, can enable smaller effective pixel size. In this case, the lower limit drops to 2.0 or even 1.5 μm, but even that size is not small enough to meet both the resolution and size requirements for high-end endoscopy applications. The higher the resolution, the more accurately physicians can diagnose patients based on endoscopic images. High resolution is also critical for surgical applications. Required pixel counts for 4K2K (2160 x 3840) imaging cannot be achieved without either shrinking the pixel size or increasing the chip size.

Power consumption concerns for medical image sensors, unlike for consumer electronics, are not related to battery life. The critical issue is heat generation at the distal tip of the endoscope, which must never exceed 43° Celsius. The small size of endoscopes does not allow space for mechanical heat sinks, so power consumption must be low enough for device operating temperature to stay in a safe range.

Chip size concerns aside, 4K resolution requires four times the number of pixels as 1080p. For CCD technology, this increases power consumption from 250 milliwatts (mW) to 1 Watt per chip. Power consumption per pixel must drop to avoid excessive heat while the endoscope is inside the body.

CCD devices output analog pulses, which limits the data transfer rate. Real-time video at a high frame rate in vivo is required for smooth blur-free images.

CMOS: The Next Logical Step

CMOS image sensors are the next logical step for endoscope manufacturers facing the limits of CCD image sensors. CMOS technology is not new—it leverages a well-established, reliable semiconductor manufacturing process—but it may be unfamiliar to medical device companies that are accustomed to CCD technology.

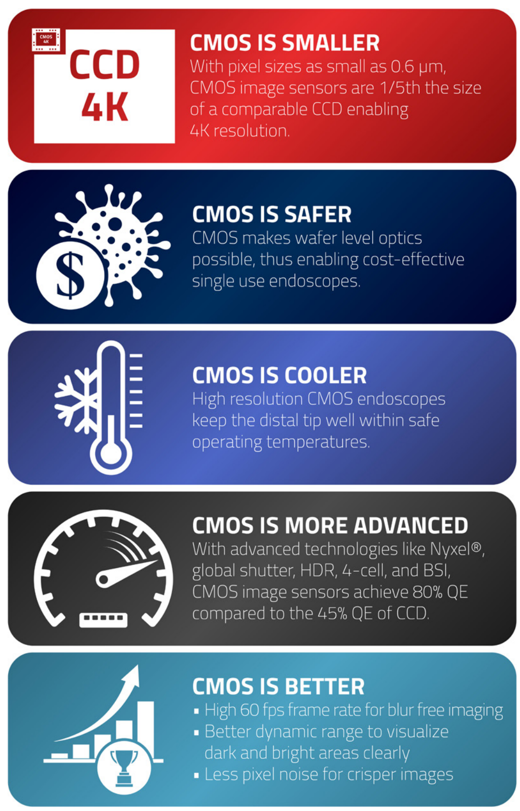

Figure 2—CCD and CMOS capability comparison.

The drive to achieve greater computing power in a smaller footprint has motivated continual advances in CMOS capabilities. Chip cost has also dropped significantly in the past decade. Image sensors based on CMOS technology leverage these advances, enabling low cost, smaller size, lower current consumption with better image quality and feature set.

The introduction of backside illumination (BSI) significantly increased quantum efficiency (QE) of CMOS image sensors. The greater the QE, the larger the fraction of incoming photons that are converted into a signal. Whereas a QE of 45% was standard for both CCD and CMOS sensors twenty years ago, today's CMOS sensors with BSI achieve 80% QE.

CMOS image sensors overcome the limitations facing CCD, the first of which is image resolution. Pixel sizes are below 1 µm, with 0.7-µm sensors in mass production. We expect the smallest pixel size in the future will go down to 0.5 µm. The decrease in pixel size allows for extremely small sensors with 1080p or 4K2K resolution. There is no longer the need to sacrifice chip size or resolution for small-diameter endoscopes.

CMOS image sensors benefit from digital output capability. High frame rates of 60 frames per second (fps) for full-resolution images and up to 240 fps for smaller images enable high-quality, blur-free imaging.

Power consumption is another reason to migrate to CMOS image sensors, especially for endoscopic surgery. The lengthier and more complex the procedure, the more important it is to limit the temperature of the distal tip. Because CMOS image sensors consume far less power per pixel than CCD sensors, even a high-resolution endoscope working at a high frame rate can remain at a safe operating temperature.

Finally, the reason to switch to CMOS is to meet the demand for applications that require specifications that CCD technology cannot achieve. Unlike with CMOS, manufacturers are not investing in advancing CCD technology.

The System Perspective

The image sensor is only one of five primary elements of an endoscope. To fully understand the advantages of CMOS image sensors, it is helpful to consider the entire system.

In addition to a high-resolution image sensor, endoscopes need:

- A light source to illuminate the area of interest
- A lens to focus the light from the source
- Cabling to connect the various elements and transmit data
- An image signal processor (ISP) to convert the input from the sensor into viewable images

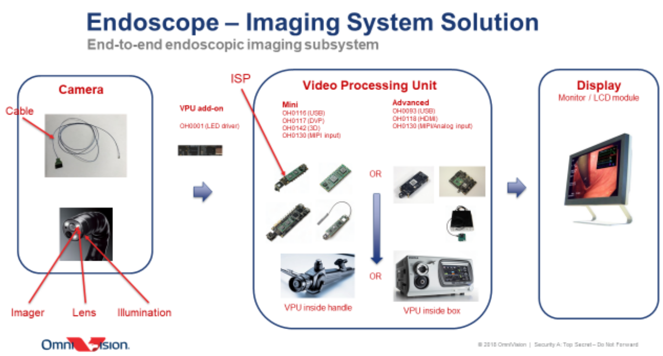

Figure 3—Endoscope system.

An integrated system (Figure 3) should be optimized so that all components work well together. See the sidebar for more details on the key design parameters for each element.

CMOS image sensors enable a simpler system with fewer components. With CCD technology, the image sensor usually resides in the endoscope handle. CCD technology, therefore, requires a driver chip separate from the sensor.

CMOS image sensors are located on the distal tip of the endoscope. Placing the image sensor at the distal tip results in better quality images as well as a more compact system. With CMOS, it is possible to integrate multiple functions, including the ISP, in a single chip. Doing so reduces system cost and size, streamlines inventory control, and simplifies the supply chain.

Making the Switch

Converting from CCD to CMOS requires retrofitting the camera system. Since CCD-based endoscope towers are expensive equipment that last 10 to 15 years, the best time to make the switch is when the system needs replacing. It is not necessary to replace the entire tower, only to swap out the endoscope and camera control unit.

Many traditional CCD suppliers are exiting the market. As a result, availability of CCD sensors will decline in the coming years. The market for CMOS image sensors, in contrast, is growing sharply because of demand from multiple industries [1].

Because CMOS image sensors leverage low-cost CMOS fabrication process, prices are constantly declining. The small size of the sensors means that tens of thousands of sensors are fabricated in parallel on a single wafer. The smaller the chip (the world's smallest commercially available image sensor (figure 4) measures 0.6 mm on a side) means there are more chips per wafer, which also lowers the cost [2].

Design Considerations for Implementing CMOS

Optics

Whether illumination comes from light-emitting diodes (LEDs) or fiber optic cables, endoscope optics must meet multiple performance specifications for optimum image quality. Designers should consider optical parameters such as image circle size, color aberration, distortion, and resolving power.

The field of view (FoV) must be wide enough to allow full image display regardless of the working distance. For this reason, FoV is defined by angle rather than linear distance, with the type of endoscope determining the ideal angle.

The F-number (F/#) of the lens should be optimized to balance the desired specifications for optical resolution, depth of field, and illumination.

In addition, the chief ray angle (CRA) of the lens needs to match the CRA of the imager for optimum image quality. Antireflective coatings are essential, and infrared cut-off filters are often recommended. Lens materials should be hard enough to withstand any mechanical impact from flying debris that might occur during surgical procedures.

Signal Integrity

The cables that are soldered to the image sensor transmit signals from the distal tip to the back of the endoscope. These cables must be thin and flexible, with enough mechanical strength to withstand the manufacturing process and the significant bending that occurs during use.

To ensure signal integrity, cables must be adequately shielded to minimize electromagnetic interference (EMI) and maximize the signal-to-

Figure 4—OMNIVISION holds the Guinness World Record for the world's smallest image sensor, pictured here.

Summary

Endoscope manufacturers need to be ready for the phase-out of CCD image sensors. While the technology was state-of-the-art 20 years ago, that is far from the case today. For both existing and emerging applications, CMOS image sensors offer multiple advantages compared to CCD technology.

New endoscopes that incorporate CMOS image sensors are necessary to compete in a rapidly evolving endoscope landscape. Both hospitals that are replacing older systems and small clinics that are introducing endoscopy to their list of services will benefit. They can provide better patient care with state-of-the-art imaging capability.

Some applications already require the advantages of CMOS image sensors: high resolution, small size, low cost, and low heat generation. Others require the portability that disposable endoscopes offer. But the full spectrum of possibilities includes emerging applications for both diagnosis and treatment.

noise ratio (SNR). Appropriate termination will avoid impedance mismatch that would degrade image quality.

ISP Requirements

The ISP controls exposure and gain, frame rate, and image processing. It should be able to process the incoming image via either a MIPI or analog interface and output via DVP, MIPI, USB, or HDMI. The ISP must be small enough to fit inside the endoscope handle or within the camera control unit (CCU).

ISPs for endoscopes must meet the safety and performance guidelines in the IEC 60601 standard for medical electrical equipment. Ideally, the ISP will offer advanced features such as high dynamic range (HDR), excellent sensitivity to both visible and near IR light, and security enhancements. Low power consumption is also desirable.

Image Sensor Features

Medical image sensors need to be RoHS and REACH certified, biocompatible, and autoclavable. They are available as chip scale packages (CSP), ready to be soldered directly onto a printed circuit board.

A rolling shutter architecture with backside illumination (BSI) is preferred. Compared to conventional front side illumination, BSI allows more light to reach the sensor, resulting in high image quality even while shrinking the pixel size.

One example of an integrated CMOS-based imaging system for endoscopes is OMNIVISION's CameraCubeChip®. This device is biocompatible, sterilizable, and waterproof. It requires no tuning or calibration and incorporates all the desired design features for a medical image sensor.

Most CMOS image sensors operate in the visible range of the electromagnetic spectrum, but some extend to the near infrared (NIR). Medical-grade CMOS image sensors that use an NIR light source allow surgeons to target tumors more precisely using ICG-based procedures [3].

Many medical device manufacturers want to develop state-of-the-art endoscopes that enable their customers to perform advanced diagnostic and therapeutic procedures. They cannot afford to wait until their existing equipment becomes obsolete. Upgrading from CCD to CMOS technology now is the key that will allow them to deliver on this promise.

References

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