Series: High-frame-rate imaging–toward a camera that clearly captures fast moving subjects

This series of four articles introduces our research on a new image sensor capable of capturing clear images of fast moving subjects.

Overview of High Frame-rate Imaging Technology

Hiroshi Ohtake, Senior Research Engineer, Imaging & Storage Devices Research Division

The number of images per second in a video sequence is called the frame rate (unit: frames per second). A higher frame rate, that is, a higher time resolution for moving images, makes it possible to attain clearer and smoother video reproductions, even for a fast moving subject. The frame rate for the current Hi-Vision (HDTV) system is 30 frames/second (interlaced scanning: 60 fields/second). The next generation of ultrahigh-definition broadcasting (e.g., full-spec SHV system) may have up to 120 frames per second (progressive scanning) for better video image quality. The Science & Technology Research Laboratories (STRL) has been engaged in developing a new image sensor to make this system a reality.

Work is also advancing to enable new forms of video expression, through the construction of an ultrahigh-speed image sensor that can capture split-second phenomena that are not perceivable to the human eye and a camera system that will incorporate such an image sensor. An ultrahigh-speed single-chip color CCD with a driving speed of 1 million frames/second was developed, and a prototype camera based on this device was constructed. Replaying video clips taken with this camera using a standard television frame rate can produce clear, super-slow motion video of a fleeting event and has become a useful tool in sports and science program production. We are improving the sensor's performance by constructing an ultrahigh-speed CCD with a new structure capable of being driven at 2 million frames per second.

This series will present reports on STRL's high-frame-rate imaging technology, with examples of full-spec. SHV image sensor and ultrahigh-speed CCD applications. It will also describe the recently launched three-dimensional image sensor. This sensor has a signal processor and output circuit placed directly under the pixel area to read out the signals from every pixel in parallel. It is hoped that this sensor will attain both a high frame rate and ultrahigh definition and lead to the construction of an advanced image sensor.

The three future articles will feature related studies on the ultrahigh-speed CCD, 3D image sensor, and full-spec SHV image sensor, in that order.

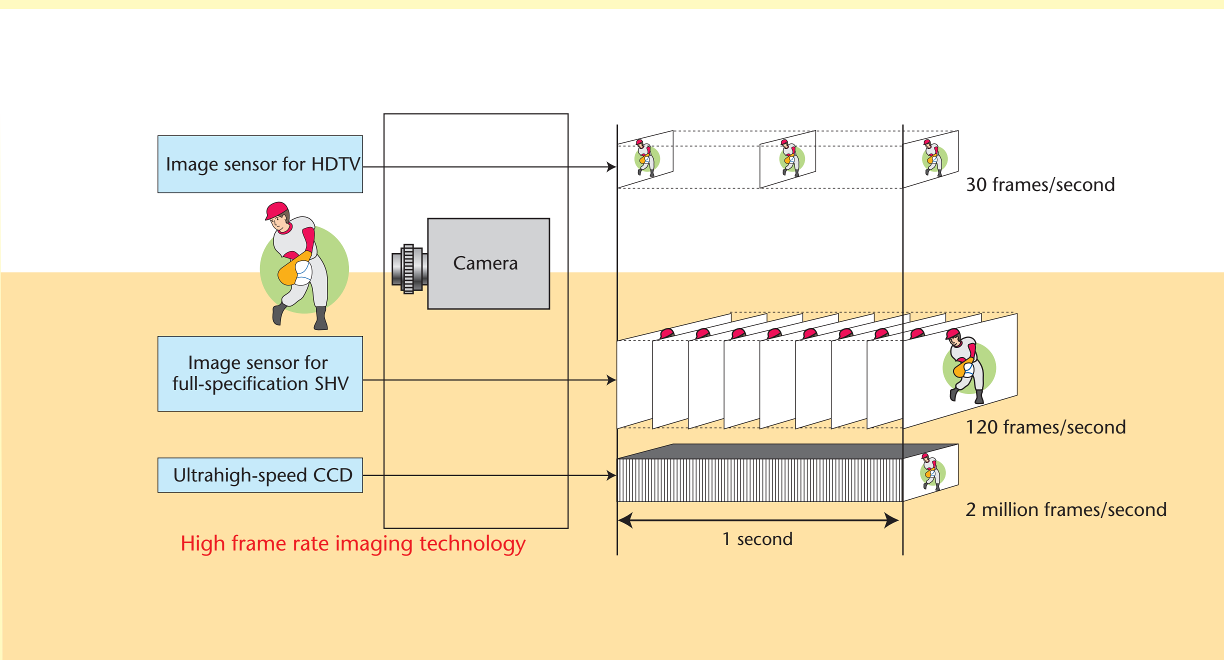
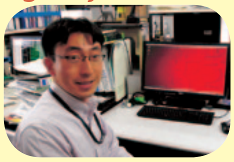


Figure: High frame rate imaging technology overview

Series: High-frame-rate imaging—toward a camera that clearly captures fast moving subjects

Ultrahigh-speed CCD Technology

Toshiki Arai, Imaging & Storage Devices Research Division



A high-speed camera can reproduce slow-motion video of phenomena that are too fast to be perceived clearly with the naked eye. Such cameras have been utilized in various fields including broadcasting, academia, and industry.

The Science & Technology Research Laboratories has been developing an ultrahigh-speed CCD and camera system with an extraordinarily high frame rate. It is capable of capturing split-second phenomena that had been too fast to capture in the past. This ultrahigh-speed CCD differs from ordinary CCDs by its utilizing an in-situ memory for each pixel (Figure 1). Every memory is directly connected to a photodiode*. The charges generated at the photodiodes, which are the image pixel data, are transferred to the memory sequentially in short intervals when shooting. Following the shoot, the data recorded in the memory are read-out at the TV standard frame rate to produce super-slow-motion video. We have constructed an ultrahigh-speed single-chip color CCD with a capability of shooting 1-million frames per second and a camera that contains this CCD. The camera system is being used for a wide range of programming genres such as sports and science programs. It was the first camera to capture the moment lightning begins to form (Figure 2).

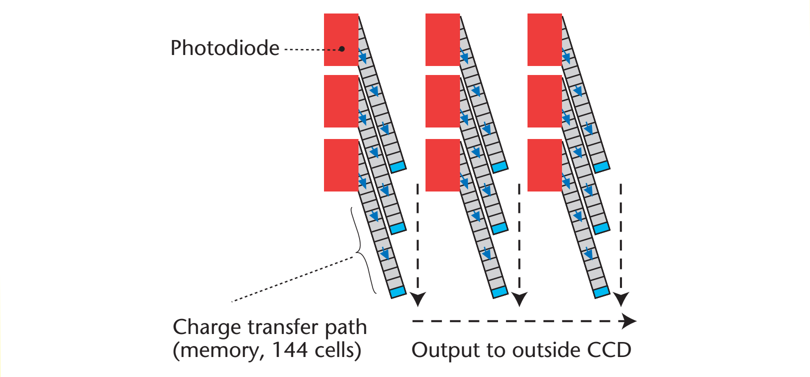


Figure 1: Ultrahigh-speed CCD structure

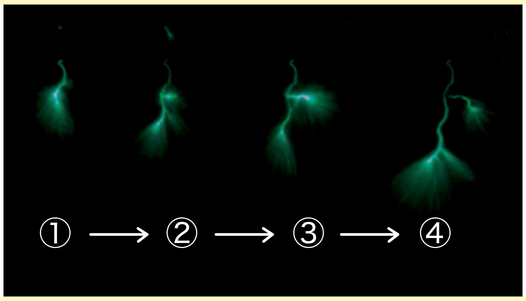


Figure 2: Lightning discharge captured with ultrahigh-speed camera (frame rate: 1 million fps)

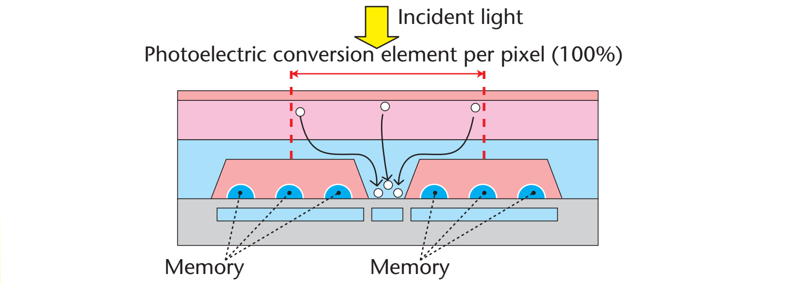


Figure 3: Back-side-illuminated ultrahigh-speed CCD cross-sectional view

We are in the process of enhancing the camera's performance through the development of a new CCD with back side illumination. The current ultrahigh-speed CCD has a memory inside each pixel and suffers from low sensitivity because it uses only about 16% of the incident light. The back-side-illumination structure (Figure 3) places the memory under a photoelectric conversion element, enabling nearly 100% of the incident light to be used. The potential sensitivity enhancement is six times or more. It also enables a relatively flexible wire design, which helps to suppress control signal attenuation and delay in the wire. This opens the prospect of doubling the frame rate to 2 million fps.

We will proceed with the construction of a prototype back-side-illuminated CCD, with the goal of creating an ultrahigh-speed camera system that meets the demands of shooting a wide range of subjects.

*Photodiode: Part of a CCD imaging device in which the incident light is converted into an electrical signal.

Series: High frame rate imaging -toward a camera that clearly captures fast moving subjects

3D Integrated Image Sensor

Kei Hagiwara, Principal Research Engineer, Imaging & Storage Devices Research Division

A dynamic, smooth motion picture cannot be attained without using ultrahigh-definition, high-frame-rate camera system. With this aim in mind, STRL is working on a new image sensor that incorporates a three-dimensional structure.

Current image sensors contain pixels and signal processing circuits on the same plane and use a single signal processing circuit per column of pixels (Figure 1). The signals from each column of pixels are read out sequentially with a single frame. These signals are then output externally via the signal processing circuit. The increased pixel count in a column for higher definition imaging shortens the signal processing time allotted to a single pixel, and this presents a problem as to how we can maintain or increase the frame rate. On the other hand, a 3D integrated image sensor processes signals from each pixel simultaneously and in parallel.

As shown in Figure 2, the signals generated at each pixel are sent to the signal processing circuit located directly below it and are output from the bottom of the sensor. This sensor is, in principle, free from any restriction from the pixel count on its signal processing time, and it is capable of attaining both ultrahigh definition and a high frame rate. The absence of wiring and circuits to deliver the signal on the device surface frees up area for a larger photodetector that would have higher sensitivity.

As a first step toward the construction of a 3D integrated image sensor, we are developing a transistor* that transfers the signals generated at each pixel from the upper layer of the device to the lower layer (Figure 3). We fabricated the prototype-transistor for operational testing purposes, and we confirmed that it could take a signal from the front side of the device and output it from the back side. We also verified that the operational characteristics that were equivalent to those of conventional transistor.

In the future, we will try to reduce the size and increase the level of integration of the transistor. We will also develop technology to stack these transistors.

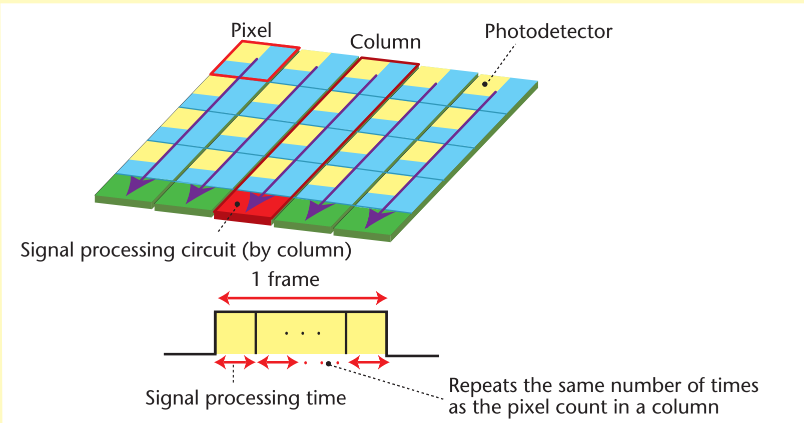


Figure 1: Current image sensor

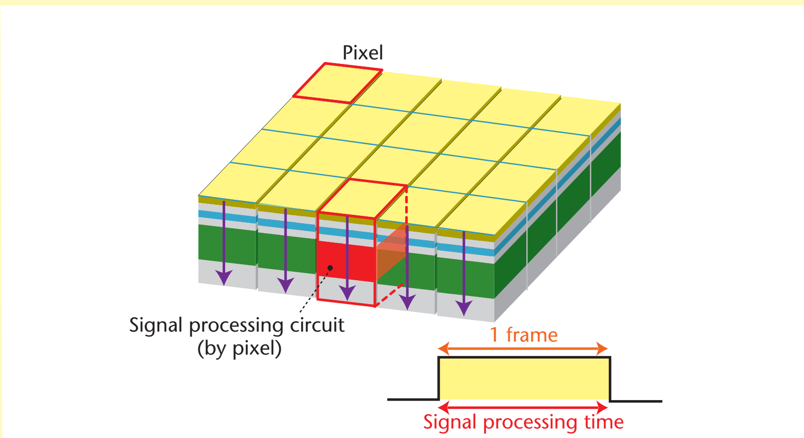


Figure 2: 3D integrated image sensor

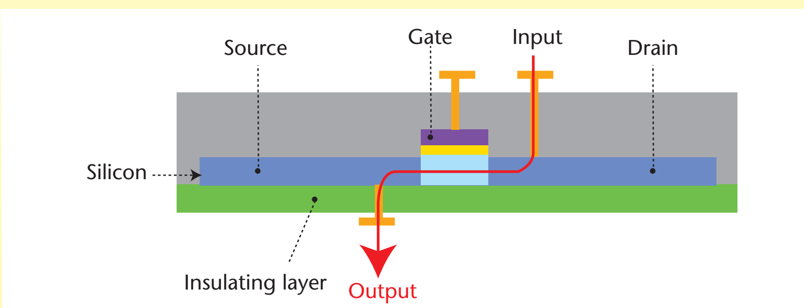


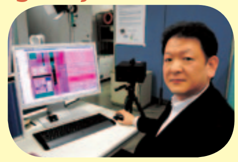
Figure 3: Structure of the transistor (cross-sectional view)

* This research is being jointly carried out with the University of Tokyo.

Series: High frame rate imaging -toward a camera that clearly captures fast moving subjects

Image Sensor for Full-spec Super Hi-Vision (SHV)

Toshihisa Watabe, Principal Research Engineer, Imaging & Storage Devices Research Division



The Science & Technology Research Laboratories have been researching and developing Super Hi-Vision (SHV), an ultra-high definition television to be part of a next-generation broadcasting system. The parameter values for full-spec SHV video signals[*1] are 33-million pixels and 120 frames per second. We recently designed and fabricated a prototype image sensor for full-spec SHV[*2].

The image sensor has one A/D (analog-to-digital) conversion circuit per column of pixels. Analog output signals of the pixels are read out sequentially from each column during one frame period. The signals are then converted into digital signals by the A/D conversion circuit and output. Compared with HDTV, the full-spec SHV system has four times the number of pixels in each column and four times the frame rate, thus requiring an A/D conversion circuit that is 16 times faster.

To meet these specifications, we developed two-stage cyclic A/D conversion circuit and fabricated a prototype image sensor using this circuit. This circuit is capable of high-speed operation and can potentially be made relatively compact. High-speed operation, while maintaining low power consumption and noise, is made possible by dividing the circuit into two parts that operate in parallel and simultaneously converting analog signals from two pixels into digital signals.

This prototype image sensor has a diagonal imaging area of approximately 25 mm, and it has 33 million pixels and a frame rate of 120 fps (progressive scanning). An evaluation experiment revealed that the prototype sensor can pick up vivid images even of a fast-moving subject, as shown in Figure 2.

We will improve the prototype sensor's sensitivity to make a full-spec SHV camera system to produce various programs.

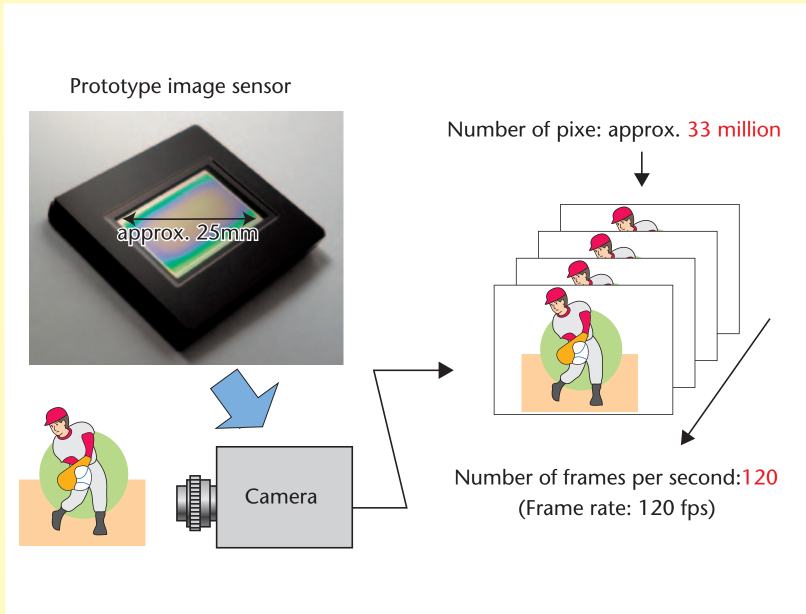


Figure 1: SHV high frame rate video technology overview

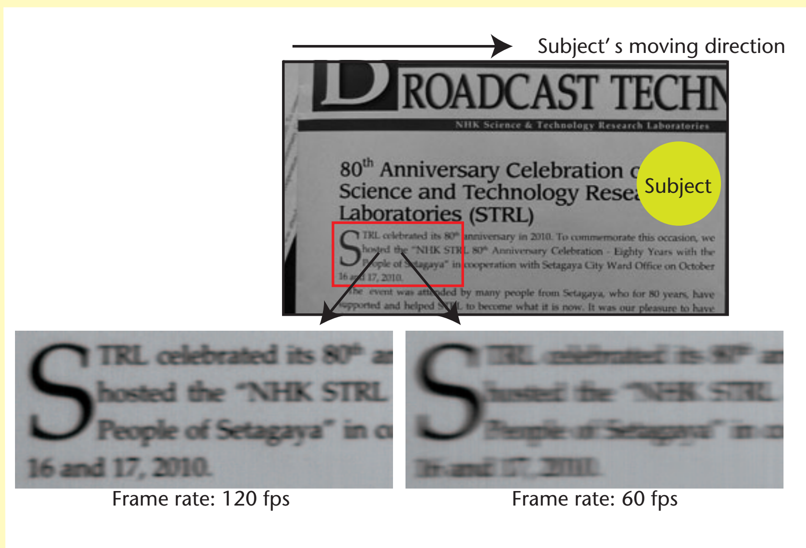


Figure 2: Sample images of a moving subject at 60 fps and 120 fps

*1 7680×4320 pixels, 120 frames per second, progressive scanning, 12-bit resolution, wide spectrum RGB color system

*2 This research is being carried out in collaboration with Shizuoka University.