Trends in Research on Ultra-high-sensitivity Imaging Devices

The technologies that go into ultra-high-sensitivity imaging devices has been growing in importance because they may lead to general-purpose imaging devices having higher temporal and spatial resolutions. Moreover, reporting breaking news of disasters and accidents is an important mission of NHK, and a compact ultra-high-sensitivity camera would be ideal for such situations. Ultra-high-sensitivity cameras are also potential energy-saving devices: they can help to reduce electricity used for lighting used in regular TV program production.
Here, we outline trends in research and development of ultra-high-sensitivity imaging devices. We also describe the latest research on high-gain avalanche rushing amorphous photoconductor (HARP) imaging devices and their applications.

1. Introduction

Charge coupled devices (CCDs) are compact, stable, and reliable, and they are widely used in high definition television (HDTV) cameras for broadcasting. The signal-to-noise ratio of an HDTV camera with 2/3rds inch[1] CCDs is 54 dB under illumination of 2000 lx and with a lens iris setting of F10. Such a camera can take clear images under ordinary lighting conditions. However, a compact camera with much higher sensitivity is required in many situations encountered when reporting breaking news at night.

We have been developing an ultra-high-sensitivity photoconductive film called HARP[1),2)] that utilizes an internal avalanche multiplication effect in a thin film composed mainly of amorphous selenium. The HARP imaging device incorporating this film has the following characteristics that give it light-sensitivity and picture-quality advantages over other ultra-high-sensitivity imaging devices.

(1) All of the incident light passing through the optical lens reaches the HARP film (a fill factor[2] of 100%).

(2) Charges generated in the film by the incident light are multiplied with low additional noise.

This article describes trends in the research and development of ultra-high-sensitivity imaging devices. The latest research results for HARP imaging devices and applications are also presented.

2. Trends in R & D on Ultra-high-sensitivity Imaging Devices

Table 1 lists typical ultra-high-sensitivity and high-sensitivity imaging devices. Imaging devices with functions for amplifying incident light or multiplying photo-generated charges are defined as ultra-high-sensitivity imaging devices, whereas devices that do not have multiplier or amplifier functions but still promise higher sensitivity than ordinary imaging devices are defined as high-sensitivity imaging devices

Typical ultra-high-sensitivity imaging devices are as follows.

(1) Electron multiplying CCD[3)] (E.M.CCD), in which photo-generated electrons are multiplied by a factor of about 1000 through the repetition of impact ionization[3] in the horizontal CCD (Figure 1).

(2) HARP imaging device, in which photo-generated charges (holes) are multiplied by the internal avalanche multiplication effect in a thin film composed mainly of amorphous selenium (a maximum charge multiplication factor of about 1000 for a 35-μm-thick film).

(3) Electron bombardment CCD[4)] (E.B.CCD), in which a photo-cathode converts incident light into electrons, and the electrons are accelerated by applying a voltage of several kilovolts. A multiplication factor of over 1000 is achieved by bombarding the electrons onto a back-side illuminated CCD (Figure 2).

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[1] Diagonal length of imaging area is 11 mm.

[2] A proportion of amount of light reaching photoelectric conversion area to total amount of incident light.

[3] A phenomenon in which new electron-hole pairs are generated when a charged particle accelerated by a high electric field loses its kinetic energy.

[4] An electron multiplication device with an array of microchannels. Electrons that enter each channel are multiplied by secondary electron emissions, which occur when they hit and cause the emission of other electrons in the wall of the channel.

Table 1: Types of ultra-high and high-sensitivity imaging devices

Device Type	Ultra-high-sensitivity imaging devices		High-sensitivity imaging devices
Means of increasing sensitivity	Impact ionization or avalanche multiplication	Other multiplication	High fill factor
Solid state image sensor	Electron multiplying CCD	Electron bombardment CCD	Back-side-illuminated CMOS image sensor Organic single-chip color imaging device
Vacuum imaging device	HARP imaging device	Image intensifier CCD (vacuum - solid state imaging device)	

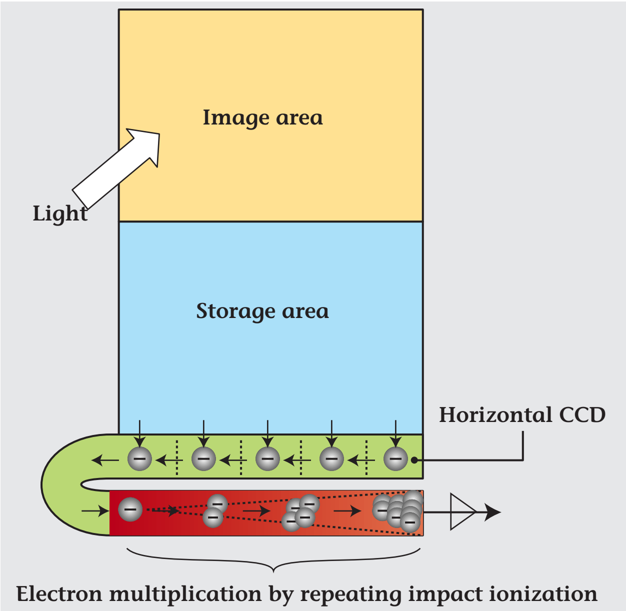


Figure 1: Structure of electron multiplying CCD (E.M.CCD)

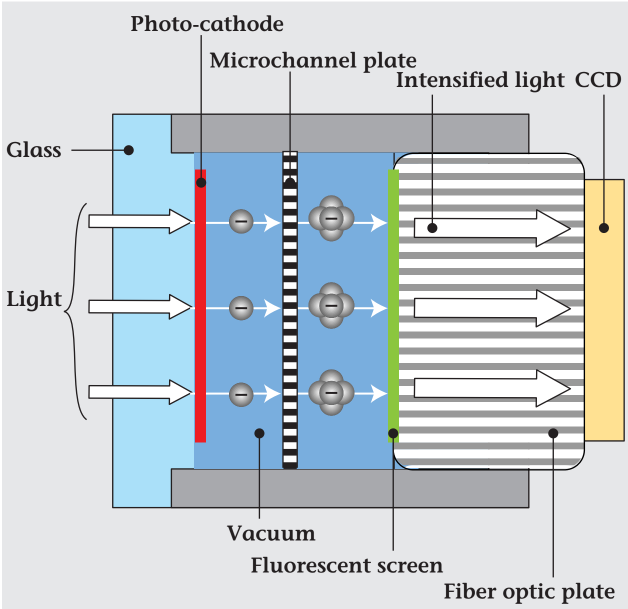


Figure 3: Structure of image intensifier CCD (I.I.CCD)

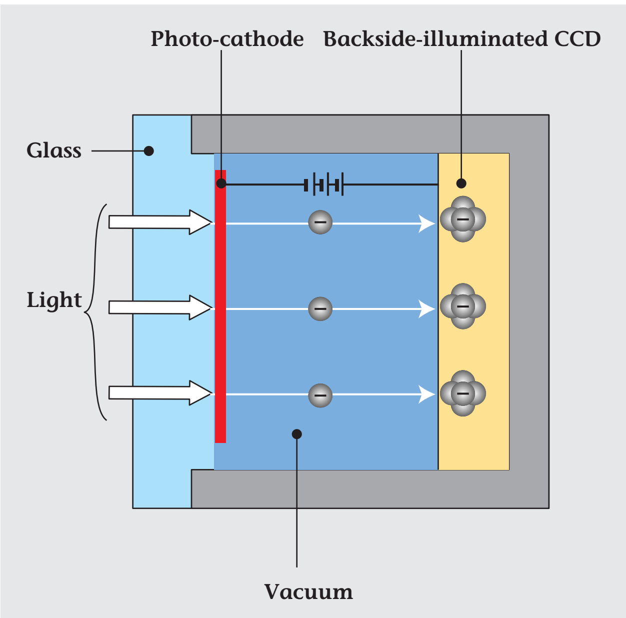


Figure 2: Structure of electron bombardment CCD (E.B.CCD)

(4) Image intensifier CCD[5] (I.I.CCD), in which a photo-cathode converts incident light into electrons, and the electrons are multiplied by a factor of up to 10,000 through a microchannel plate[4]. A video signal is obtained by shooting a fluorescent screen irradiated with the multiplied electrons (Figure 3).

In ultra-high-sensitivity imaging devices mentioned above, the E.M.CCD and the HARP imaging device are more prevalent because the I.I.CCD and the E.B.CCD have several problems such as insufficient photo-cathode conversion efficiency and burning of the photo-cathode by strong incident light. The applied voltage required for single impact ionization in the E.M.CCD is from 15 V to 20 V, and the electron multiplication factor is only from 1.01 to 1.02. A total electron multiplication factor of about 1000 is achieved by repeating this process 400 times. Although the E.M.CCD has a sensitivity that far exceeds that of an ordinary CCD, it has picture-quality problems stemming from fluctuations in electron multiplication, high dark current, and insufficient dynamic range. In contrast, the HARP imaging device

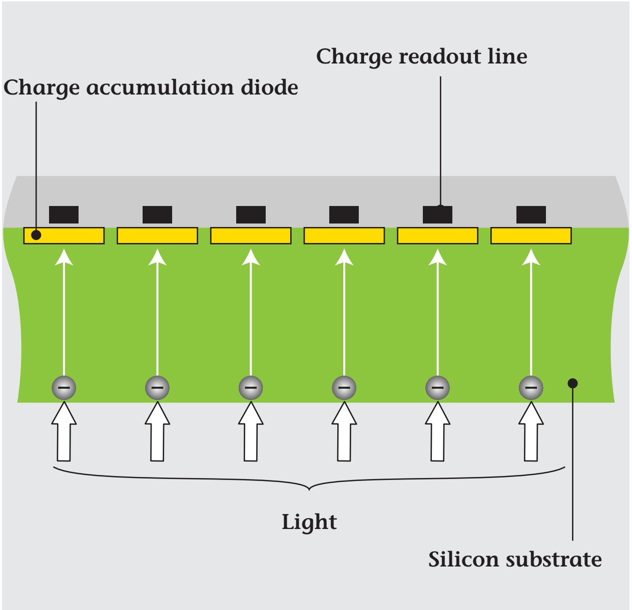


Figure 4: Structure of back-side-illuminated CMOS image sensor

attains both ultra-high sensitivity and high picture quality because it has a fill factor of 100%, low dark current, charge multiplication with low additional noise, and good reproduction of gradations of dark and light subjects. The HARP camera tube itself is relatively bulky and it consumes a lot of power. To overcome these drawbacks, we have been developing a power-efficient compact version (see section 4).

Progress on commercially viable high-sensitivity imaging devices is being led with the development of back-side-illuminated metal-oxide-semiconductor (CMOS) image sensors[6]. Light enters the back side of a silicon substrate, where it generates electrons. On the top side of the substrate are charge accumulation diodes and charge readout lines that pick up the electrons that reach them (Figure 4). The main virtue of this sensor is that it has a high fill factor. Also under development is an organic imaging device with an alternately stacked structure of three organic photoconductive films that are individually sensitive to only one of the primary color components and transparent signal readout circuits. This device can in principle convert all of the incident light into a color video signal, and it is seen as a potential next-generation single-chip color imaging device because it can obtain higher sensitivity and picture quality compared with current single-chip color imaging devices with color filters (For more information on the organic imaging device, see "Trends in Organic Imaging Device Research" in this issue.

3. HARP Camera Tube and its Applications

The HARP film and ultra-high-sensitivity camera tube containing are continuously being improved. Ultra-high-sensitivity HDTV camera tubes with 15-μm-thick and 35-μm-thick HARP films have already been developed. The maximum charge multiplication factor of the 15-μm-thick HARP film is about 200, whereas it is about 1000 for the 35-μm-thick film. The camera tubes have respectively 30 times and 200 times the sensitivity of an ordinary CCD. Our current development is to make HARP camera tubes with better color reproduction characteristics and low-voltage operation. So far, we have developed HARP films with higher photoelectric conversion efficiency[5] for long-wavelength light (red light) and films with higher multiplication efficiency.

Here, we shall discuss HARP films that have high photoelectric conversion efficiency for long-wavelength light and their camera tubes. We will also briefly describe ultra-high-sensitivity HDTV cameras that incorporate these devices and their applications.

3.1 High-efficiency HARP camera tube

Our aim is to develop ideal ultra-high-sensitivity imaging devices that satisfy the following requirements:

(1) All of the incident light reaches the photoelectric conversion area (fill factor of 100%)

(2) All of the light that enters the photoelectric conversion area is converted into electrical charges (photoelectric conversion efficiency of 100%).

(3) Charges generated by the light are multiplied without additional noise.

The current HARP camera tube almost satisfies requirements (1) and (3), so we have concentrated on making a film and camera tube that satisfy requirement (2).

Although the photoelectric conversion efficiency of the HARP film is about 100% for blue incident light, photoelectric conversion efficiency is lower for longer wavelengths because the band gap of amorphous selenium, which is main component of the HARP film, is rather wide (about 2.0 eV). The lower efficiency for long-wavelength light in turn leads to poor color reproduction and a low signal-to-noise ratio. To solve this problem, particularly for red light, a high-efficiency HARP film doped with tellurium (Te) having a narrower band gap (0.34 eV) was developed and applied to the red channel of a three-HARP-tube color camera. However, the efficiency for red light (wavelength of 620 nm) of conventional high-efficiency HARP film was only 11%. Experiments suggested though that the photoelectric

[5] Proportion of charges generated by a single incident photon.

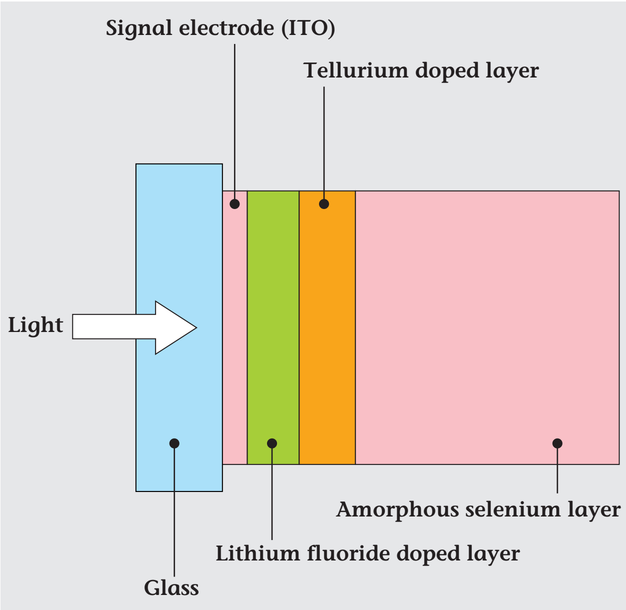


Figure 5: Structure of high-efficiency HARP film

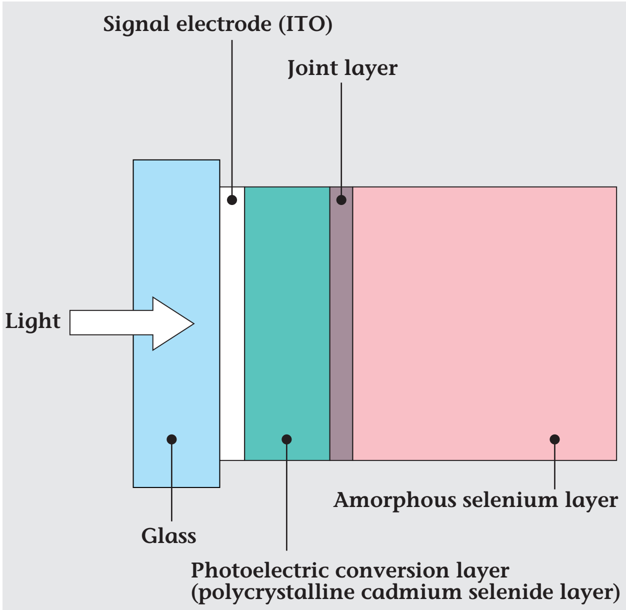


Figure 7: Structure of next-generation high-efficiency HARP film

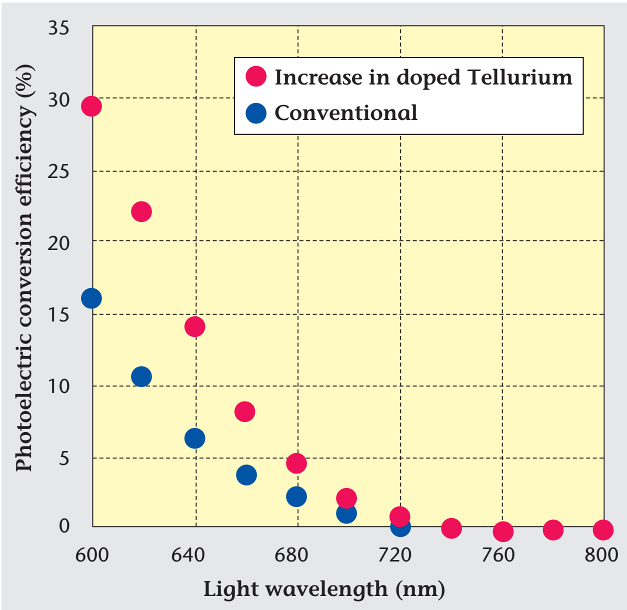


Figure 6: Photoelectric conversion efficiency improved by increasing amount of tellurium

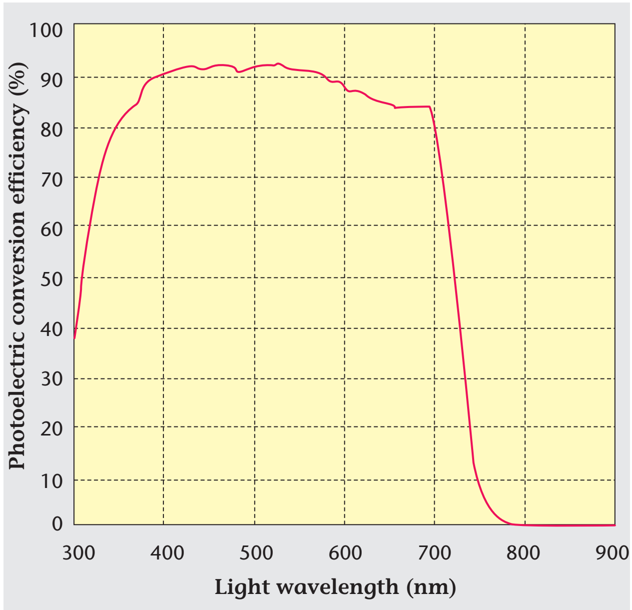


Figure 8: Photo-electrical conversion efficiency of fabricated next-generation high-efficiency HARP film

conversion efficiency for long-wavelength light could be improved by increasing the amount of tellurium dopant in the film. The problem in this case is that increasing the dopant ratio causes local concentrations in the electric field of the film, which in turn increases dark current and the occurrence of defects. To solve this problem, the specifications of a lithium fluoride doped layer shown in Figure 5, which plays the role of dissipating local concentrations of the electric field, were revised[8),9)]. As a result of these changes, the photoelectric conversion efficiency for red light (620-nm wavelength) was increased from 11 % to 22% without increasing dark current or the occurrence of defects (Figure 6).

We have been developing a next-generation high-efficiency HARP film with a photoelectric conversion efficiency of nearly 100% for the whole visible light spectrum in parallel with our efforts to improve the efficiency for long-wavelength light. The next-generation high-efficiency HARP film illustrated in Figure 7 consists of a new photoelectric conversion layer that has high efficiency for the entire visible light spectrum, an amorphous selenium layer for avalanche multiplication, and a joint bonding these two layers. This film uses polycrystalline cadmium selenide (CdSe) as its photoelectric conversion material. Experiments on it revealed that the charges generated in the cadmium selenide layer by incident light stably reached the amorphous selenium layer, and the film had high photoelectric conversion efficiency for the entire visible light spectrum (Figure 8)[10]. Although the charge avalanche multiplication in the amorphous selenium layer was insufficient, the photoelectric conversion efficiency was nearly 100%. Sufficient charge avalanche multiplication should be able to be achieved by applying an electric field of about 10^7 V/m to the cadmium selenide layer and an electric field of about 10^8 V/m to the amorphous selenium layer. We are now developing technologies to control the electric fields of the two layers.

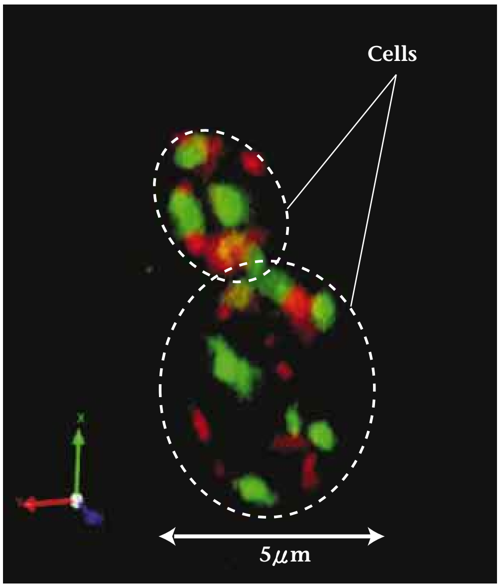
3.2 Ultra-high sensitivity HARP camera and its applications

Figure 9 shows a hand-held HDTV HARP camera using 2/3rds-inch HARP camera tubes with 15-μm-thick HARP films (a charge multiplication factor of about 200). The maximum sensitivity of the camera is over 30 times that of an ordinary hand-held HDTV CCD camera, and its sensitivity can be varied among eight levels. By using the amplifier gain control and the lens iris control with the sensitivity control, the camera can deal with the wide range of lighting conditions experience during daytime and nighttime. Furthermore, the camera has circuits and a frame memory for intermittent readout from the camera tubes: This gives the camera very high effective sensitivity when shooting a subject that is still or in slow-motion.

We have also developed a hand-held HDTV HARP camera using 2/3rds -inch HARP camera tubes with 35-μm-thick HARP films (multiplication factor of about 1000). Its sensitivity is over 200 times that of an ordinary HDTV CCD camera. Such cameras have been used in reporting breaking news at night. For instance, NHK used it in its coverage of nighttime rescue work after the Niigata Chuetsu earthquake. It has also been used to shoot nocturnal animals and northern lights.

Aside from broadcasting, the HDTV HARP camera has been utilized in various fields, for example, natural science, medical science, and biology. In the natural sciences, the camera has been used for deep-sea exploration because lighting does not reach far in water. In particular, the camera with a parallel optical system was mounted on the Hyper-dolphin unmanned submersible for deep sea exploration (maximum depth of 3000 m) that belongs to the Japan Agency for Marine-Earth Science and Technology to act as a sensitive underwater "eye" [11]. The Hyper-dolphin was used to investigate the epicenter region of the Sumatra earthquake in the deep sea and its images revealed large-scale cracks on the seabed. The HARP camera has also been used in medical and biological applications, for shooting microvessels in order to evaluate the efficiency of therapeutic angiogenesis and for shooting living cells to analyze the mechanism of protein trafficking. Regarding the former use, since there was no practical way to visually evaluate microvessels generated by therapeutic angiogenesis, researchers at the National Cardiovascular Center developed an in-house micro-

Figure 9: Ultra-high-sensitivity hand-held HDTV HARP camera



(Source: RIKEN)

Figure 10: Example of three-dimensional color image of Golgi cisternae (red and green parts are Golgi cisternae)

angiography system equipped with an HDTV HARP camera as an x-ray detector. The system could shoot motion pictures of microvessels with a diameter from 50 μm to 200 μm, which is difficult to accomplish with a conventional angiography system. The system is being utilized as a unique clinical diagnosis system to evaluate therapeutic angiogenesis for patients suffering from arteriosclerosis obliterans. Regarding the latter, since living cells have to be observed at very short time intervals in order to clarify the protein trafficking mechanism, a new confocal laser scanning microscopic system with the HDTV HARP camera (over 200 times the sensitivity of an ordinary CCD camera) was developed by the RIKEN Discovery Research Institute. By using this high temporal and spatial resolution microscopic system, Akihiko Nakano et al. took three-dimensional color images of Golgi cisternae, as shown in Figure 10, and clarified[12)] the mechanism of protein trafficking through the Golgi bodies[6]. This microscopic system, which enables direct nano-scale imaging of live cells, will contribute to answering a variety of questions in life sciences. Thus, HARP imaging technology is not limited to broadcasting; it has uses in various parts of society.

4. Field Emitter Array (FEA) Imaging Device with HARP Film

We have been developing a compact and low-power HARP imaging device called an FEA-HARP to overcome the camera tube problem described in section 2 [13), 14)]. The FEA-HARP (Figure 11) consists of an FEA that is an X-Y matrix array of small field emitters, a mesh electrode, and a HARP film in close proximity to each other. The FEA acts as an electron source, and the mesh electrode accelerates electrons emitted from the field emitters. The film converts incident light into electric charges (holes) and multiplies them by using the internal avalanche

6 One of the organelles involved in sorting and trafficking proteins produced in a cell.

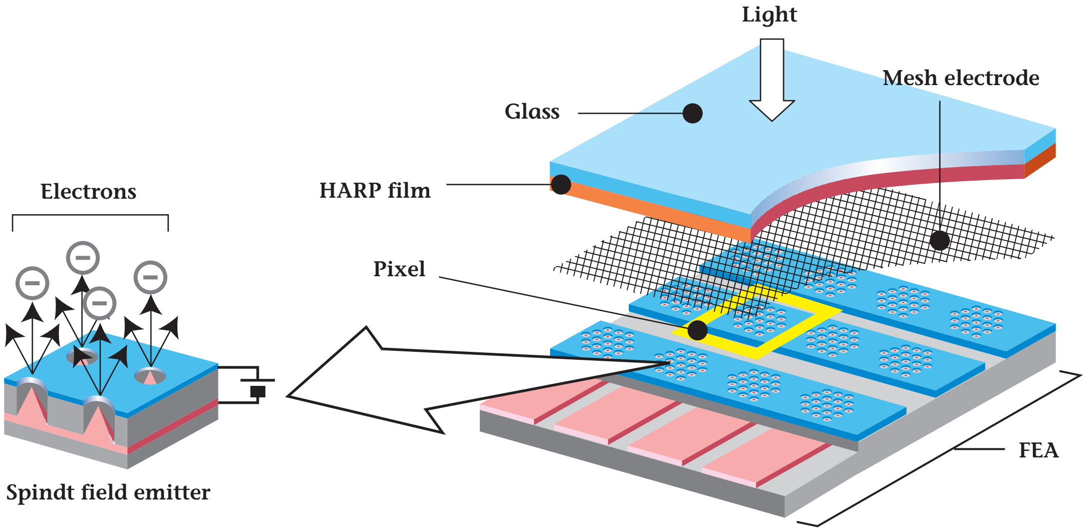


Figure 11: Structure of FEA-HARP

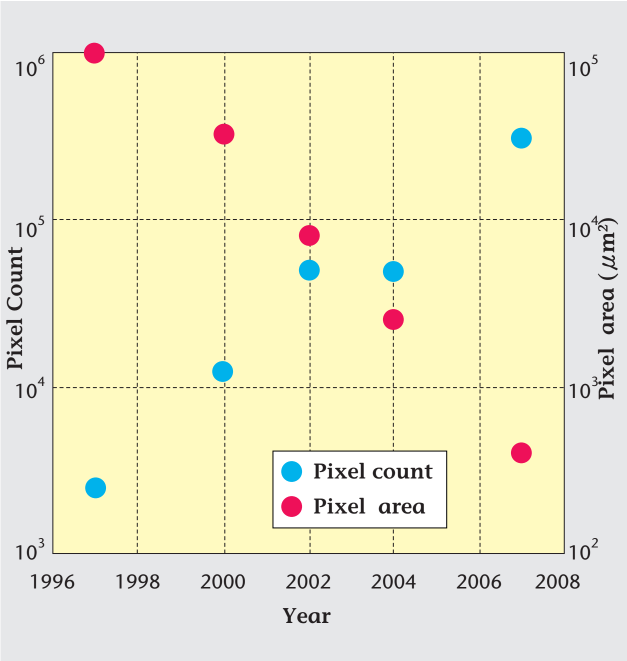


Figure 12: Progress in pixel integration of FEA-HARP

multiplication effect. A video signal is obtained, pixel-by-pixel, by recombining the holes accumulated on the film and the electrons emitted from each pixel[7] of the FEA. This method is different from the one used in the HARP camera tube where the video signal is obtained by scanning the HARP film with a single electron beam emitted from an electron gun. The FEA-HARP may be ideal for reporting breaking news at night because it can maintain the high picture quality and ultra-high sensitivity even when strong light enters it during a shot in otherwise low light conditions. We have been developing the pixel integration with a Spindt FEA[8] and with a high-efficiency electron emission device (HEED) FEA (Figure 12). In this section, we outline our latest VGA format HARP with a Spindt FEA.

The VGA format FEA-HARP consists of a 20 × 20 μm pixel active-matrix Spindt FEA with 640 × 480 pixels, a mesh electrode, and a 15-μm-thick HARP film (maximum multiplication factor of about 200). The previous FEA-HARP with a passive-matrix Spindt FEA could not operate at high speed and many wires between the FEA and external drive-circuits were required for driving it because it was directly driven by applying drive pulses from external drive circuits, which limits the number of pixels. These problems were solved through the development of a new Spindt FEA with built-in active matrix driving circuits consisting of a metal-oxide-semiconductor (MOS) transistor formed in each pixel and horizontal and vertical scanning circuits placed outside the pixel area (Figure 13). High-speed operation was achieved by switching the cathode potential of the Spindt field emitters in each pixel via the MOS transistor. A dramatic reduction in the number of connecting wires was also realized by using the internal horizontal and

[7] Minimum unit for which electron emission can be controlled.

[8] An X-Y matrix array of Spindt field emitters. Each Spindt field emitter consists of a cone-shaped cathode and a gate electrode surrounding a cathode.

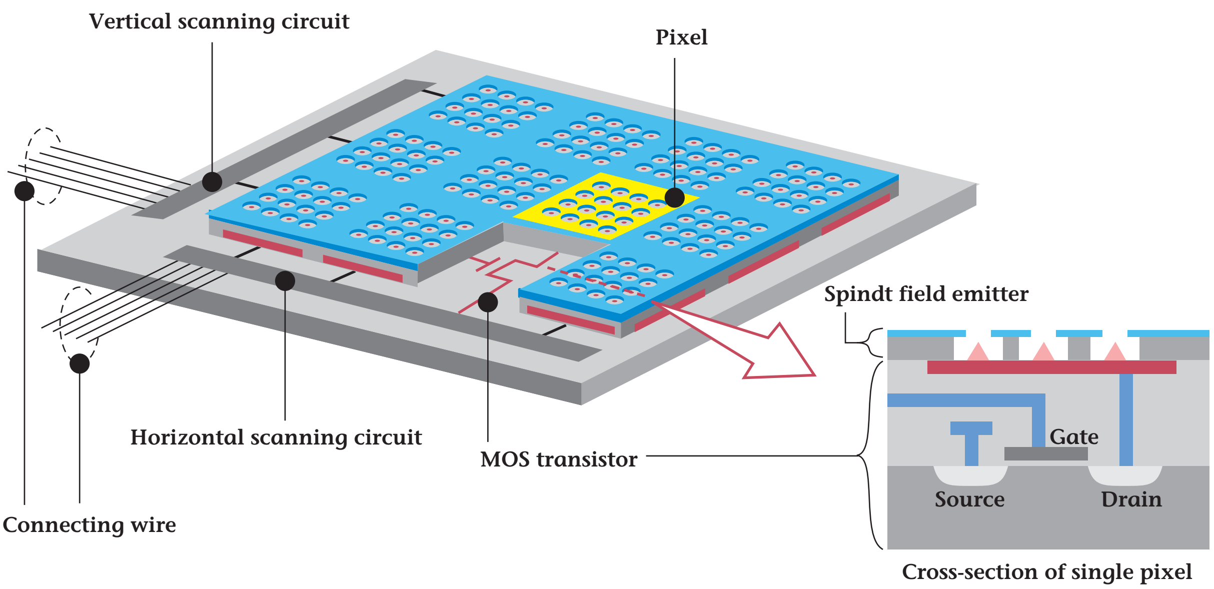


Figure 13: Structure of active-matrix Spindt FEA

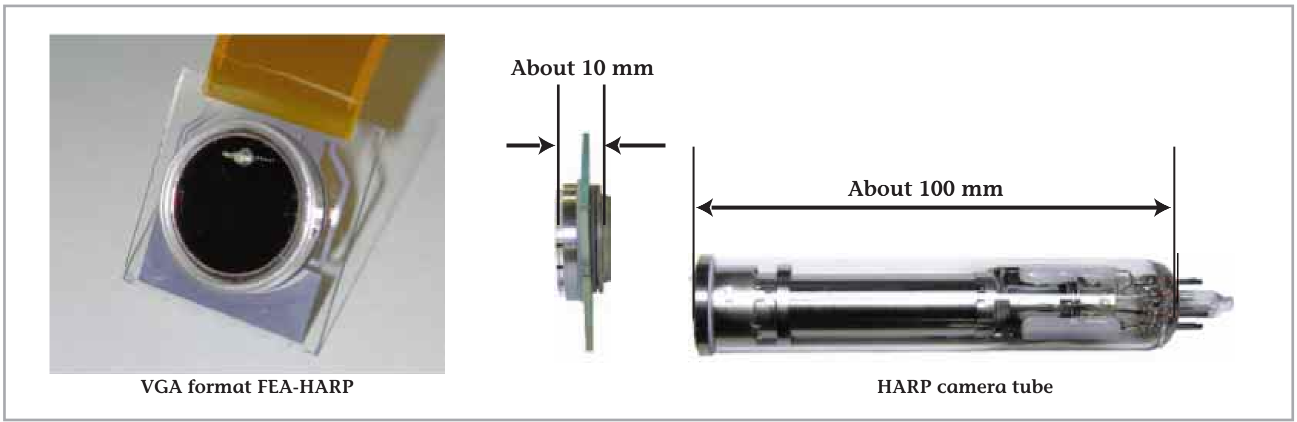


Figure 14: VGA format FEA-HARP

vertical scanning circuits that control the MOS transistors in the pixel area by using the external clock, synchronization signals, etc. The active-matrix Spindt FEA contributed to the VGA format FEA-HARP by making it possible to use much smaller pixels. Unfortunately, the emitted electrons have a large spatial spread that would prevent the FEA-HARP from having a high enough resolution for VGA format. A magnetic focusing system consisting of two types of neodymium permanent magnets was developed for devices with 20 × 20 μm pixels. Figure 14 shows the developed VGA format FEA-HARP (without the magnetic focusing system), and Figure 15 shows images taken by it with the magnetic focusing system under an illumination of about 0.3 lx and a lens iris setting of F1.2. The 10-mm-thick VGA format FEA-HARP with a 15-μm-thick HARP film could produce clear images even under dim lighting conditions such as moonlight. The image was of similar quality as one from a 100-mm-long HARP camera tube using film of the same thickness. The VGA format FEA-HARP thus had

Figure 15: Reproduced image taken by VGA format FEA-HARP (illumination of about 0.3 lx, lens iris setting of F1.2)

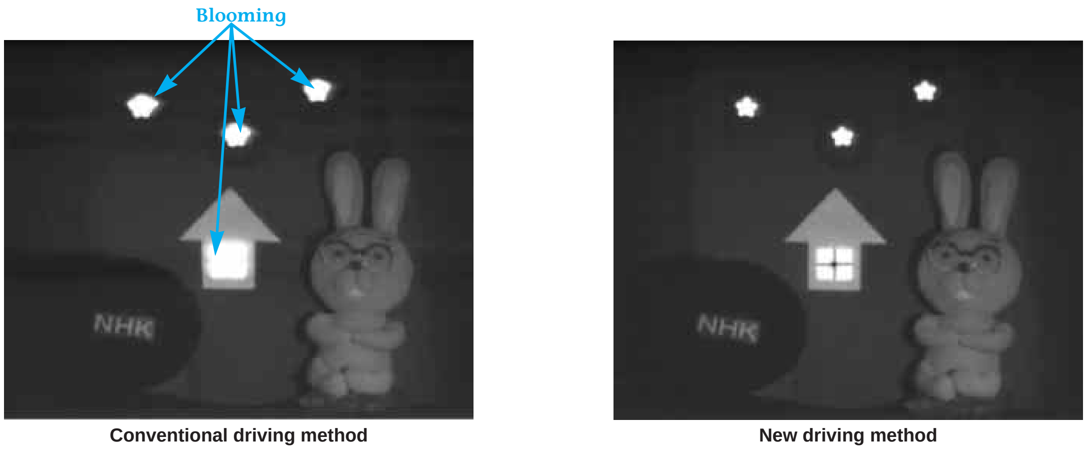


Figure 16: Comparison of image qualities when strong light enters FEA-HARPs using different driving methods

enough resolution for its pixel size and its power consumption was less than 1/10th that of a HARP camera tube.

The HARP camera tube and previous FEA-HARP had another problem: the appearance of spurious images called blooming, in which a high luminance subject appears to be bigger, and comet tails, in which a high-luminance moving subject leaves a visible trail like that of a comet. These spurious images are caused by strong incident light from sources such as streetlights and car headlights during ultra-high-sensitive shooting at night. To suppress these spurious images and to obtain higher picture quality, we developed a new driving technology that removes any excess charges from the HARP film just before scanning by using electrons emitted from the FEA during the horizontal blanking interval. The experimental results on the FEA-HARP using this new driving method revealed that both blooming and comet tails could be suppressed even when the intensity of incident light was several hundred times that corresponding to the white level of the output video signal, and that high picture quality could be obtained in strong and weak incident light, as shown in Figure 16. The results also revealed that the output signal level of areas of strong incident light could be controlled by changing the cathode potential of the FEA. One benefit of such a feature is that it expands the range of image expression that can be used in dramatic productions.

We are now developing a compact FEA with smaller pixels and a new focusing system without permanent magnets.

5. Conclusions

We described trends in the research and development of ultra-high-sensitivity imaging devices and the latest research on HARP imaging devices.

The technologies used in ultra-high sensitive imaging are now seen as indispensable to the development of imaging devices having higher temporal and spatial resolutions. Additionally, ultra-high-sensitivity cameras are needed for reporting breaking news at night, which is one of important missions of NHK. Although ultra-high-sensitivity cameras with HARP camera tubes are now being utilized in broadcasting and various other fields, smaller cameras with higher sensitivity are required for many applications such as reporting breaking news. We will focus on developing an HDTV FEA-HARP imaging device with next-generation high-efficiency HARP film. We will also look for new applications for our cameras so that society benefits to the fullest extent from our research.

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