

## Medical Applications of Ultra-Sensitive HARP Imaging Devices

We are studying High-gain Avalanche Rushing amorphous Photoconductor (HARP) films that will be used in ultra-sensitive Hi-Vision cameras for night-time emergency reports and science programs. Devices using HARP photoconductive films are attracting attention because of their ultra-high sensitivity and excellent image quality and usefulness in other fields besides broadcasting. In this article, we introduce some of the HARP imaging device applications for the medical field and review the state-of-the-art research and development on HARP photoconductive films.

### 1. Introduction

Current broadcast Hi-Vision cameras have imaging devices using charge coupled devices (CCD) or complementary metal-oxide semiconductor (CMOS) technology. These imaging devices have adequate sensitivity and image quality under normal lighting conditions, but they do not always have adequate sensitivity when the lighting conditions are exceptionally poor, such as for night-time news reporting or filming of nocturnal animals.

At NHK STRL, we are conducting R&D on HARP photoconductive films<sup>1)2)</sup> (hereafter called HARP films), which are composed mainly of amorphous selenium ( $\alpha$ -Se) and have an avalanche multiplication effect<sup>\*1</sup>. Besides extremely high sensitivity, imaging devices using HARP film have excellent characteristics not found in other highly sensitive imaging devices, e.g., low noise, wide dynamic range, and high resolution, and they are finding uses in a wide range of fields beyond broadcasting.

In this article, we give an overview of HARP imaging devices, describe some of the applications in the medical field, and review the state-of-the-art in R&D on HARP films.

### 2. HARP Imaging Devices

Figure 1 shows a camera tube that uses HARP film, and Figure 2 outlines



Figure 1: External view of HARP camera tube

the operating principle of the film. When light enters the film, the energy of the incident light produces electron and hole pairs in the film. The holes are accelerated by a strong electric field (over  $10^8$  V/m) applied to the film, and new electron-hole pairs are successively generated by repeated impact ionization<sup>\*2</sup> with the Se atoms in the film.

As a result of this multiplication effect, many holes accumulate on the electron-beam scan side. On the other hand, an electron beam is emitted from an electron gun, and it scans the HARP film. The holes accumulated on the HARP film combine with electrons from the electron beam, and this allows current to flow. This current in turn yields a video signal from the camera tube. This operating principle implies that given a constant electric

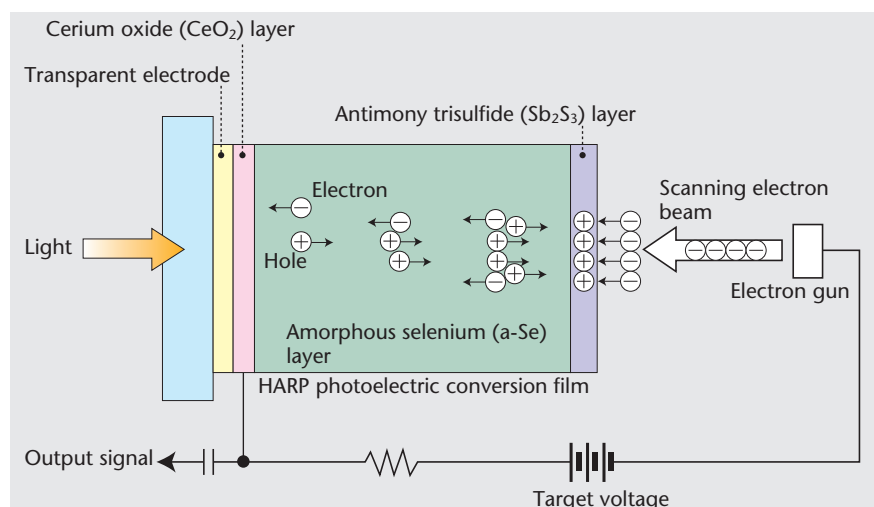
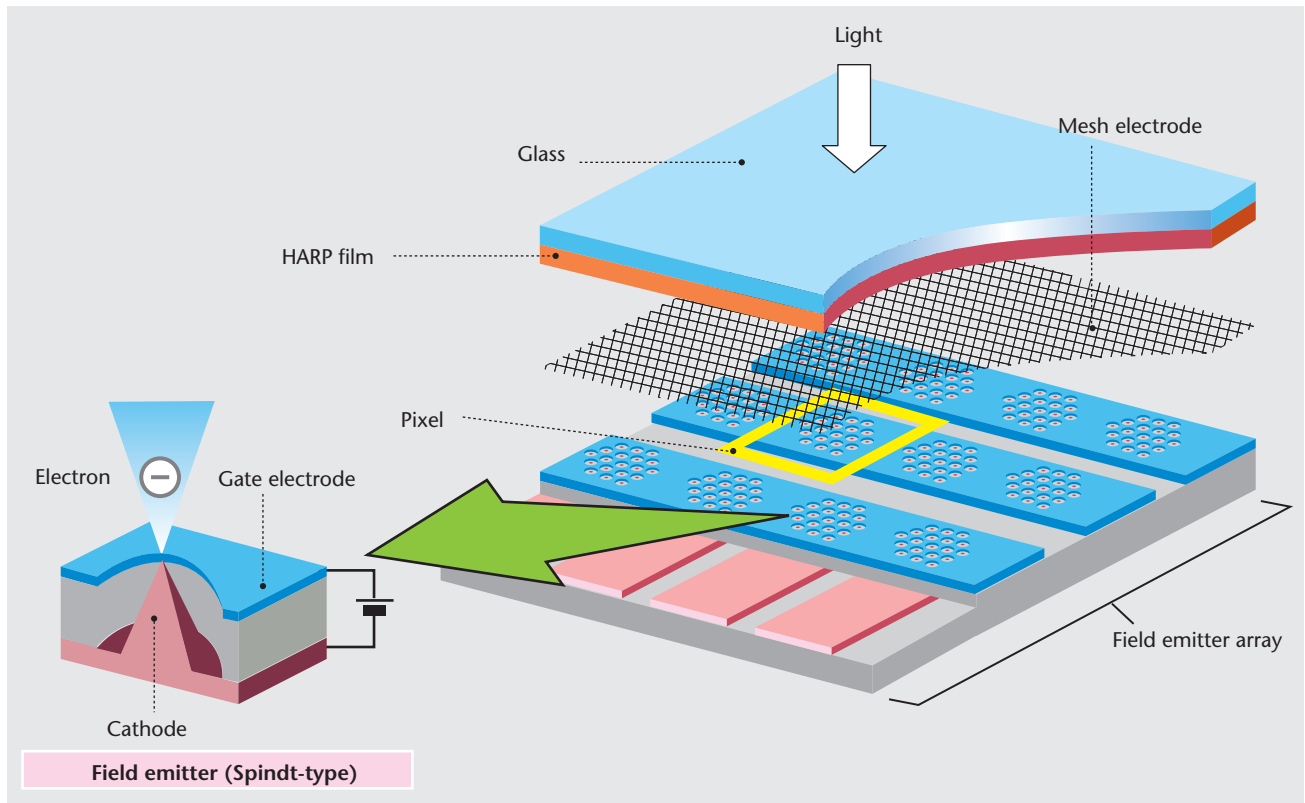


Figure 2: Operating principles of HARP camera tube

<sup>\*1</sup> An effect whereby charged particles accelerated by a strong electric field collide repeatedly with atoms, successively producing new charged particles in a way similar to an avalanche of snow.

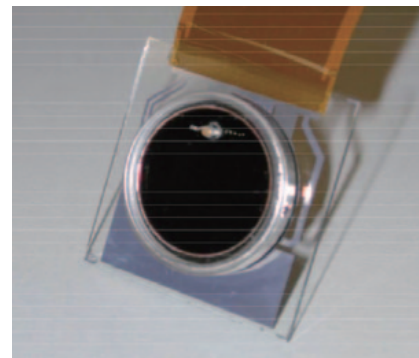
<sup>\*2</sup> An effect in which charged particles accelerated by an electric field lose energy through collisions, and generate new electron-hole pairs.



**Figure 3: Field emitter array HARP imaging device structure**

field within the HARP film, the avalanche multiplication factor will increase as the thickness of the film increases and produce higher sensitivity. At the beginning of development, we created 2- $\mu\text{m}$ -thick HARP films (with an avalanche multiplication factor of 10). The current camera tubes use 15- $\mu\text{m}$ -thick HARP films with an avalanche multiplication factor of 200<sup>3)</sup>, and we have recently prototyped an camera tube with a 35- $\mu\text{m}$ -thick film that has an avalanche multiplication factor of approximately 1000<sup>4)</sup>. Avalanche multiplication in other devices involves a relatively large amount of noise, but HARP camera tubes have very little additional noise<sup>5)</sup>. This is the most advantageous feature of HARP imaging devices.

We are developing a compact and low-power-consumption HARP imaging device that uses a field emitter array<sup>6)7)</sup>. As shown in Figure 3, the field emitter array contains many microscopic field emitters that are arranged in a plane. The array is set very closely facing a HARP film, and it emit electrons when any voltage is applied to the gate electrode. The HARP film in a camera tube is scanned with a single electron beam, whereas the HARP film of the field emitter array imaging device is scanned with the electrons emitted by the array in each pixel. Our latest field emitter array prototype consists of 640 x 480 pixels, measuring 20  $\mu\text{m}$  x 20  $\mu\text{m}$  in pixel size. The imaging device incorporates it with a 15- $\mu\text{m}$  HARP film, and it is capable of producing clear images at light levels equivalent to moonlight and with a resolution appropriate to the number of pixels (equivalent of



**Figure 4: External view of field emitter array HARP imaging device for standard-definition television**

standard-definition television, see Figure 4)<sup>8)</sup>. In contrast to a camera tube, some of the excess charge generated by the HARP film in the field emitter array HARP imaging device can be eliminated during the horizontal blanking interval by using electrons emitted by the array. This prevents false signals such as blooming<sup>\*3</sup> and comet tails<sup>\*4</sup>, from being generated, even when shooting bright objects such as automobile headlights<sup>9)</sup>. We are also

<sup>\*3</sup> A phenomenon in which objects that are very bright appear larger than their actual size in the photographed image.

<sup>\*4</sup> A phenomenon in which moving objects that are very bright leave a comet-like trail in the photographed image.

developing an electrostatic focusing system that places a focusing electrode above the field emitter array in order to make a very small imaging device with a Hi-Vision level of resolution<sup>10</sup>.

### 3. Medical Applications of HARP Imaging Devices

Applications of HARP imaging devices span a variety of fields: broadcasting, medicine, science<sup>11)12)</sup>, deep-sea exploration<sup>13)</sup>, movie production<sup>14)</sup>, and night-time surveillance<sup>15)</sup>. Here, we discuss its applications in the medical field.

#### 3.1 Micro-Angiography

For X-ray imaging of blood vessels, a contrast material is injected into the blood vessels and the differences in X-ray absorption characteristics between it and the surrounding bone and tissue show up in the X-ray image. However, as the diameter of the blood vessels decreases, the amount of contrast material in the vessels also decreases, and it becomes difficult to obtain adequate contrast for a physician to make a diagnosis.

We cooperated with the Tokai University School of Medicine and the High-Energy Accelerator Research Organization (KEK) to build micro-angiography

equipment using a HARP tube camera for imaging small blood vessels. As a result, we were able to record clear motion video of small blood vessels of diameters from 50  $\mu\text{m}$  to 200  $\mu\text{m}$  for the first time anywhere (Figure 5)<sup>16)</sup>. Based on these results, X-ray micro-angiography equipment that can be used in ordinary hospitals was developed (Figure 6), and it is being used to evaluate revascularization therapy on patients with peripheral artery occlusive disease<sup>\*5</sup> and other ailments<sup>17)</sup>.

#### 3.2 In Utero Fetus Treatments

Advances in ultrasonic diagnosis technology are making possible to diagnose disorders in a fetus earlier, and more and more in utero fetus treatments are appearing. Such treatments use an endoscope equipped with a camera and a light source. It is desirable to use as low illumination as possible to minimize any effect on the developing eyes of the fetus. Reducing the illumination also places less burden on the mother's body by limiting the temperature increase of the amniotic fluid in the uterus and enabling the use of a smaller-diameter endoscope<sup>18)</sup>. We are cooperating with the National Center for Child Health and Development to incorporate the compact field emitter array HARP imaging device discussed in Section 2 in an endoscope for in-utero fetus treatments. So far, we have shown that we can greatly reduce illumination relative to existing endoscopes equipped with CCD cameras. This new endoscope is promising way to increase the effectiveness of fetus treatments and to reverse the birthrate decline.

#### 3.3 Ophthalmic Treatments

A common treatment for cataracts, a disease in which the crystalline lens of the eye becomes cloudy and appears muddied, is to surgically replace the lens with an artificial lens. However, an artificial lens can cause undesired optical reflections, called glare, that can be perceived by the recipient of the lens when he or she is viewing a bright light source. One possible cause is reflections from the edges of the lens<sup>19)</sup>. We built the experimental system shown in Figure 7 and used a HARP tube camera to photograph this glare. Figure 8 shows an example of the resulting images. Thanks to the camera's high sensitivity and wide dynamic range, we were able to photograph both the extremely bright, desired optical-lens image and the faint, glare image at the same time. Thus, we were able to understand the dynamic relationship between the angle that light enters the lens and the production of glare, allowing us to evaluate lenses more closely conforming to reality.

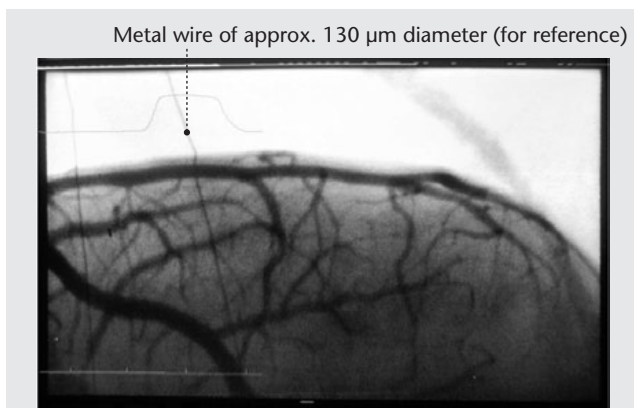


Figure 5: Example image of small blood vessels (dog heart)

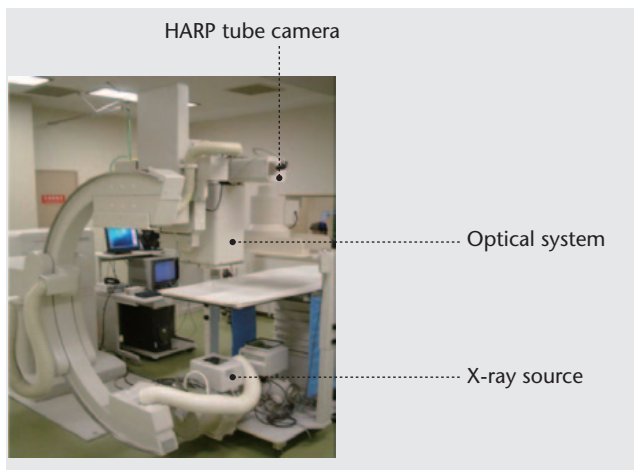


Figure 6: X-ray micro-angiography equipment for hospital use (National Cerebral and Cardiovascular Center)

\*5 A disease in which small blood vessels become blocked due to arteriosclerosis or other causes, restricting circulation of blood.

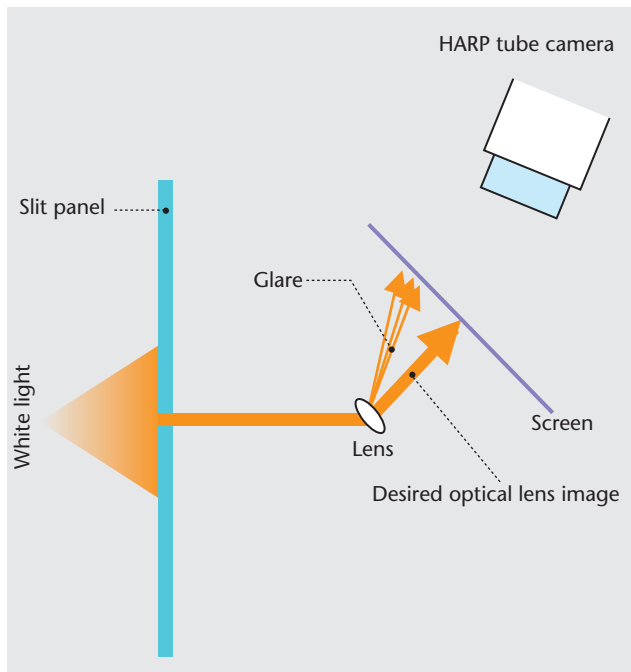


Figure 7: Glare imaging experimental system

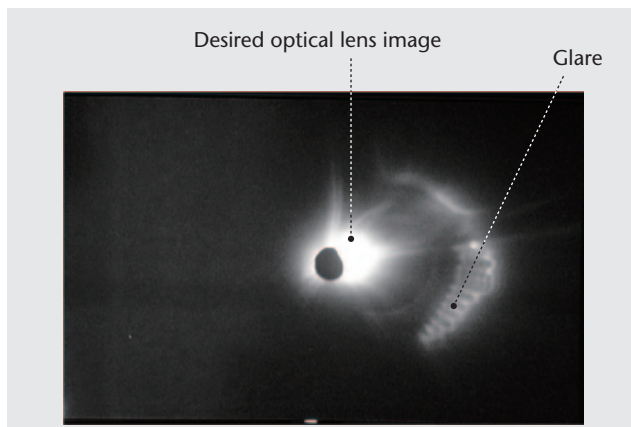


Figure 8: Glare image example (Tokyo Medical Center)

### 3.4 Bio-Research

In order to elucidate the mechanisms of phenomena occurring inside living cells, it is necessary to observe weak fluorescence\*6 over extremely short time intervals. In cooperation with RIKEN, we have developed observation equipment combining a laser confocal microscope with an ultra-sensitive HARP tube camera that is more than 100 times faster than conventional optical microscopes (Figure 9). This equipment was used to investigate an unfolding controversy among researchers around the world<sup>20)</sup> regarding the protein transport mechanism for organelles within cells called the Golgi bodies\*7. The

\*6 Light produced when substances excited by light, heat or chemical reaction lose energy and return to their original state.

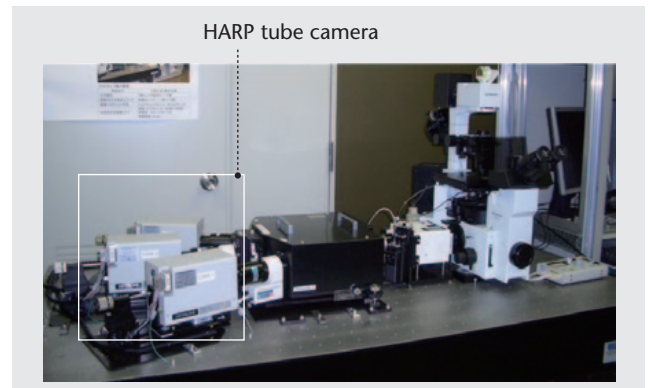


Figure 9: External view of developed bio-research microscope (RIKEN)

equipment has provided a method for observing living cells at a fine time resolution, so it is very promising for new drug development and infectious disease research.

## 4. State-of-the-art R&D on HARP Film

### 4.1 Increasing the Efficiency of HARP Films

Three conditions must be satisfied in order to realize an ideal ultra-sensitive imaging device: (1) All incident light must be guided to the photoelectric conversion component (aperture ratio\*8 of 100%); (2) All light reaching the photoelectric conversion component must be converted into electrical charge (photoelectric conversion efficiency of 100%); and (3) The charge generated by the light can be amplified without additional noise. Conditions (1) and (3) can be met with the current HARP films, and we are currently attempting to devise a way to meet condition (2).

The band gap of the main component of a HARP film,  $\alpha$ -Se, is 2.0 eV. This allows nearly 100% photoelectric conversion for shorter wavelengths (blue light), but the efficiency drops for longer wavelengths (green and red

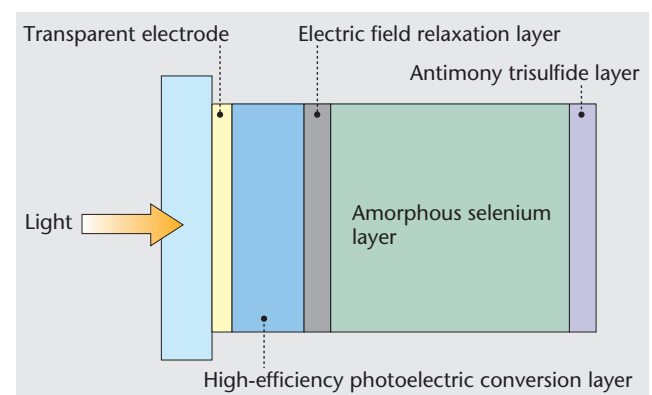


Figure 10: High-efficiency HARP film basic structure

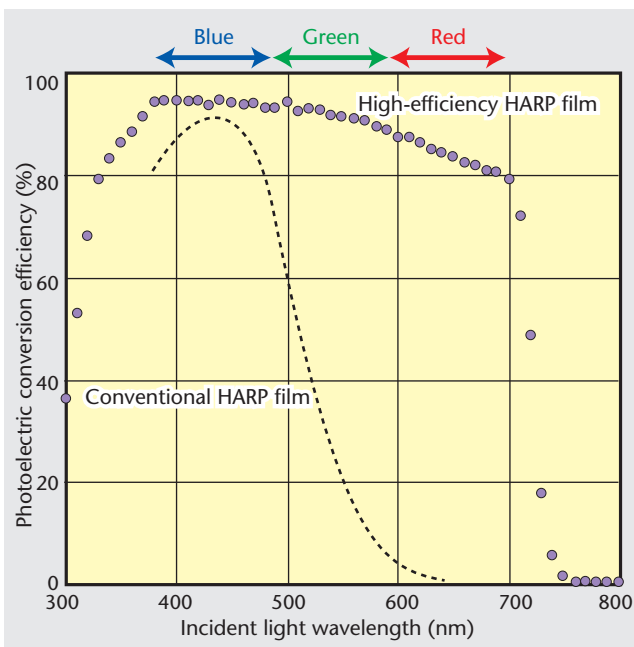
\*7 An organelle within cells which functions to classify proteins produced in the cell and dispatch them in various directions.

\*8 The proportion of light incident on an imaging device that is transported to the photoelectric conversion section.

light). Because of this, we created HARP film doping tellurium (Te), which has a band gap of 0.34 eV and easily absorbs long wavelengths of light, and used this film in the camera tube for the red channel of a three-tube color camera. The doped tellurium<sup>21)</sup>, however, caused another problem; tellurium can easily trap electrons, and as more is added, more electrons are trapped in areas around the tellurium, creating a strongly concentrated electric field that makes film defects occur more easily. This limited the photoelectric conversion that we could get with tellurium doping, so we are continuing to search

for ways to increase photoelectric conversion efficiency.

We developed a high-efficiency HARP film prototype that has a photoelectric conversion layer, with a conversion efficiency of nearly 100% across the visible spectrum, and an a-Se avalanche multiplication layer separated by an electric field relaxation layer (Figure 10). The electric field relaxation layer controls the electric fields applied to the photoelectric conversion and avalanche multiplication layers. The photoelectric conversion layer is composed of polycrystalline cadmium selenide (CdSe). Figures 11 and 12 show that the film has a high photoelectric conversion efficiency across the visible spectrum and stable avalanche multiplication<sup>22)</sup>. However, the balance between electric fields applied to the photoelectric conversion and a-Se layers a little diverges from the optimum values, and the avalanche multiplication layer is unable to produce the desired multiplication factor. Currently, we are examining the formation conditions of the electric field relaxation layer.



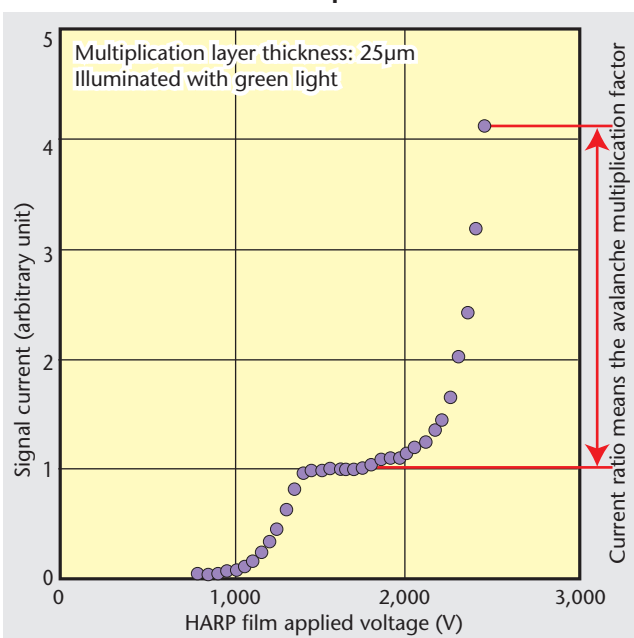
**Figure 11: High-efficiency HARP film spectral sensitivity example**

#### 4.2 Reducing the Dark Current of HARP Films

It is possible to increase the avalanche multiplication factor of HARP films by increasing the voltage applied to the film. However, when this voltage is increased, the dark current<sup>9)</sup> also increases, causing the image quality to deteriorate, so the dark current limits the voltage that can be applied to the HARP film.

The main cause of dark current in HARP films has been supposed to be external charges (electrons or holes) injected into the film. Accordingly, we put a cerium oxide (CeO<sub>2</sub>) layer between the transparent electrode and a-Se layer (Figure 2) and an antimony trisulfide (Sb<sub>2</sub>S<sub>3</sub>) layer between the a-Se layer and the electron-beam scanning side. The energy barriers formed by these layers prevent external charges from being injected. To reduce the dark current in HARP films using a hole avalanche multiplication, it is particularly important to prevent injection of holes from outside, so we are attempting to strengthen the structure formed by the transparent electrode, the a-Se layer, and the CeO<sub>2</sub> layer for preventing hole injection.

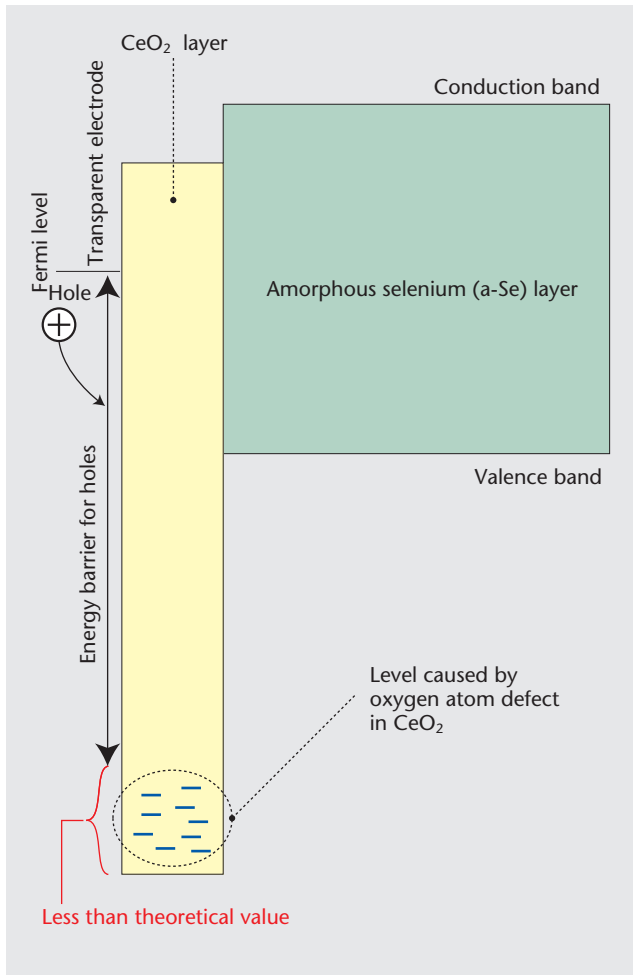
In prototype testing so far, we have learned that dark current can be reduced by heating the substrate while the CeO<sub>2</sub> layer is being formed<sup>23)</sup>. To identify the mechanism by which the CeO<sub>2</sub> layer reduces dark current, we analyzed the layer structure using hard X-rays<sup>10)</sup>. As a result, we found that there were fewer oxygen defects in the CeO<sub>2</sub> layer formed while heating the substrate compared with a layer formed without heating. By eliminating the defect level, the energy barrier was effectively increased (Figure 13) and the dark current decreased. In the future, we will develop processes to form CeO<sub>2</sub> layers with even fewer oxygen defects in order to further reduce the dark current, and we will continue to search for new materials



**Figure 12: High-efficiency HARP film current-voltage characteristic example**

<sup>9)</sup> Current flowing in the imaging device while there is no incident light.

<sup>10)</sup> X-rays with high energy and penetrating capability.



**Figure 13: Structure for preventing hole injection in HARP film (energy band diagram)**

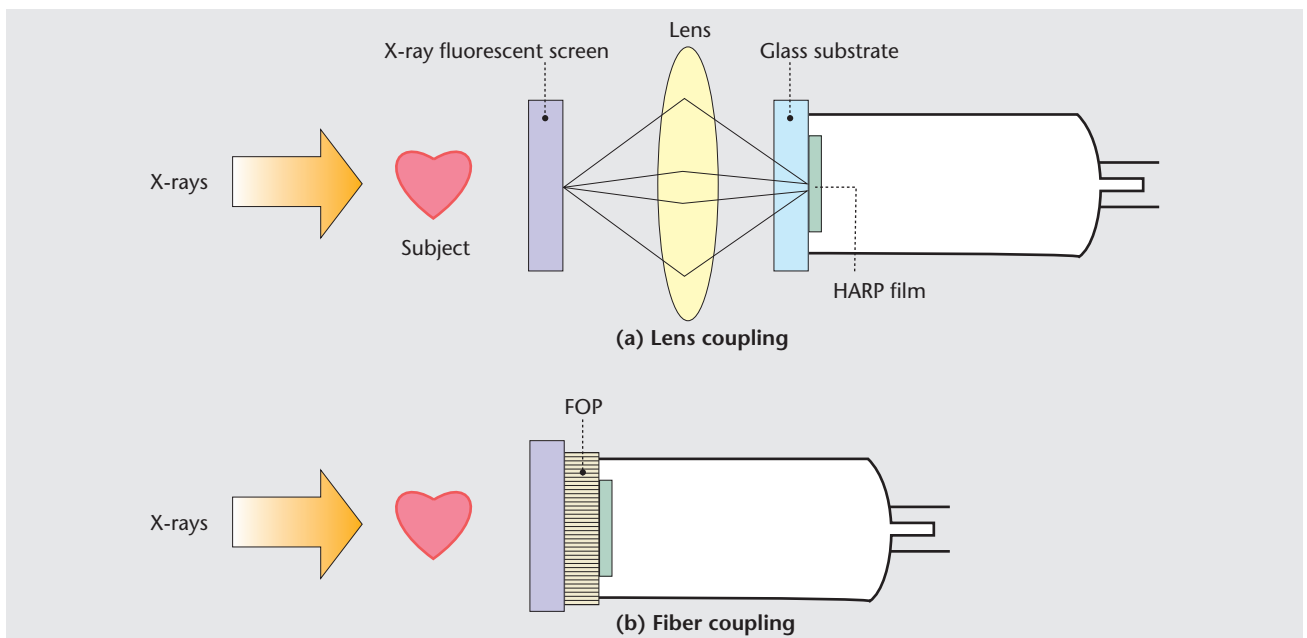
that prevent holes from being injected into the film.

**4.3 Technology for Forming HARP Films on a Fiber Substrate**

In the micro-angiography system discussed in Section 3.1, X-rays penetrating the subject strike a fluorescent screen and are converted into a visible image that passes through an optical lens system and is captured by a HARP camera tube (Figure 14(a)). A problem with this is that only a small percentage of the visible light emitted by the fluorescent screen enters the HARP film. To solve it, an optical device called a fiber optic plate (FOP), which bundles many glass fibers with several μm in diameter together, can be used to couple the X-ray fluorescent screen with the HARP film optically (Figure 14(b)). Thus, we are developing technology to form the HARP film directly on the surface of the FOP.

The substrate on which the HARP film is formed must be very flat to reduce film defects in high electric fields. However, as shown in Figure 15, the FOP is composed of three types of glass with different hardnesses and elastic coefficients\*<sup>11</sup>, called core glass, clad glass, and absorbent glass. The conventional polishing methods cannot be used to polish them to a flat surface, so we developed a new polishing technology that uses a flexible polishing disk with a urethane plate and ultra-pure water. We were able to form the HARP film on the FOP after flattening it with the new polishing method (Figure 16), and the resulting FOP-HARP camera tube had fewer film defects<sup>24</sup>. We used this camera tube in a micro-angiography system, obtaining a spatial resolution of 25 μm or more,

<sup>11</sup> A physical value indicating how easily a material is deformed when a force is applied to it.



**Figure 14: Systems coupling X-ray fluorescent screen and HARP film**

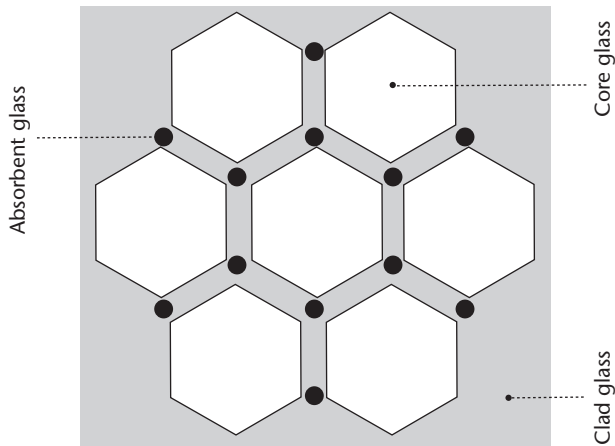


Figure 15: FOP structure

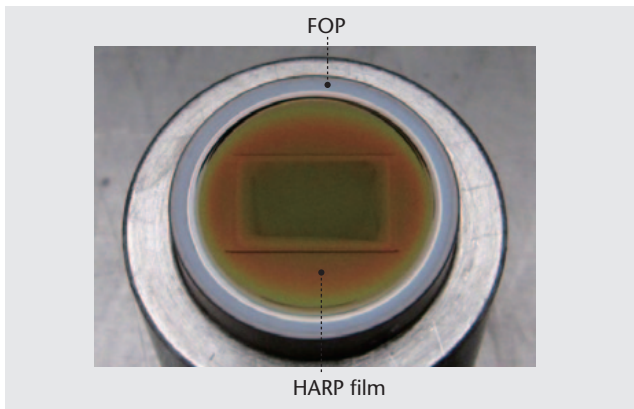


Figure 16: HARP film formed on the FOP

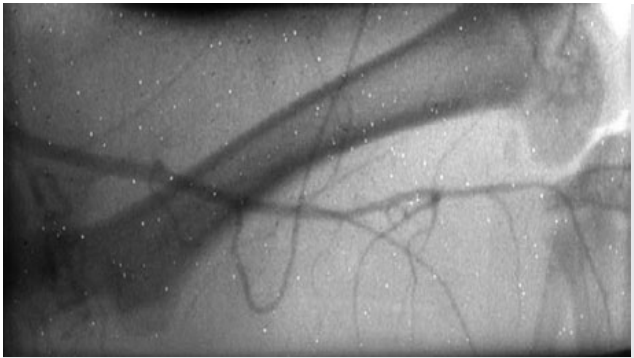


Figure 17: Rat blood vessels imaged using a low-concentration contrast material (Tsukuba University)

and when imaging blood vessels, we were able to capture video and evaluate blood vessels of diameter from 150 to 200  $\mu\text{m}$  (Figure 17)<sup>25)</sup>, even when the concentration of the contrast material had been reduced to one quarter of that used conventionally (from 32% to 8%).

Although HARP films are not sensitive to near-infrared light, ultra-sensitive near infrared imaging is possible by connecting a FOP-HARP device by fiber to, for example, a device such as an image intensifier that converts near infrared to visible light. We are currently conducting imaging experiments using a prototype camera (Figure 18), and in the future, we are hoping to use it in science

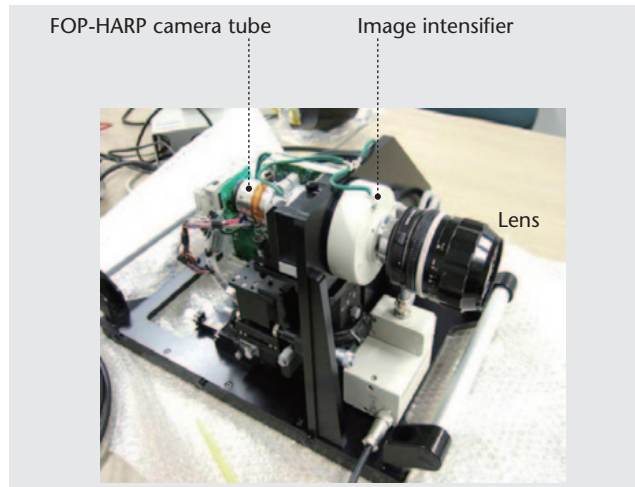


Figure 18: External view of a near-infrared imaging apparatus using a FOP-HARP camera tube

program production by filming weak near-infrared images of the night sky or of fluorescent material deep inside the human body.

## 5. Conclusion

In this article, we discussed the medical applications and state-of-the-art of R&D of ultra-sensitive HARP imaging devices that make use of the avalanche multiplication effect in photoconductive a-Se films. As a public broadcaster, NHK has been given the task of developing the ultra-sensitive imaging devices essential for emergency reporting at night time. It is also an important duty for us to put the broadcasting technology we have developed to use to advance other fields such as medicine that are directly related to the comfort and well-being of people.

Toward realizing compact, ultra-sensitive Hi-Vision cameras, we will work on developing field emitter array HARP imaging devices incorporating the next generation of high-efficiency HARP films with high photoelectric conversion efficiency across the visible spectrum. Finally, we will also continue to be proactive with our initiatives to return the results of our research to society.

(Misao Kubota and Norifumi Egami)

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