6 Devices and materials for next-generation broadcasting

We are researching the next generation of imaging, recording, and display devices and materials for new broadcast services such as 8K Super Hi-Vision (SHV).

Our research on imaging devices led to progress in developing image sensors with ultra-high sensitivity, organic image sensors, and 3D-structured imaging devices. Our work on ultra-high-sensitivity image sensors included investigating photoconductive film that multiplies the electric charge created by applying a low voltage. Its use will increase the sensitivity of ultra-high-resolution cameras. We also improved our field emitter array image sensor with high-gain avalanche rushing amorphous photoconductor (HARP) film that is used for emergency reporting at nighttime and in other low-light situations. In our work on single-chip organic color image sensors with an image quality comparable to that of three-chip color broadcast cameras, we developed elemental technologies to improve the resolution such as miniaturization of the pixel pitch of a transparent thin film transistor circuit and thinning of the interlayer insulating layers. Our work on imaging devices with a 3D structure to improve the resolution and increase the frame rate included fabricating an array of pixels to enable capture of moving images and investigating ways to improve the sensitivity and reduce the dark current.

In our research on recording devices, we continued with our development of a high-speed magnetic recording device with no moving parts and a technology for holographic recording with the large capacity and high transfer rates required for recording SHV video. Our work on magnetic recording devices included developing a technology for recording multiple magnetic domains with different magnetization directions in magnetic nanowires and combining it with the current-driven magnetic domain motion technology and magnetic domain reproduction technology that we previously developed. Thus, we demonstrated and verified the basic operation principle of our magnetic recording devices experimentally. To further increase the data reproduction speed of holographic recording technology, we developed a dual-page reproduction technology for reproducing two data pages simultaneously by using two types of polarization and demonstrated its effectiveness.

In our research on displays, we investigated multiple-division-scanning-drive displays for the SHV system and developed elemental technologies for creating ultra-flexible large-size displays with low-cost solution-based technique. For the former, we examined multiple-division-scanning-drive methods and panel structures with the aim of displaying high-quality full-specification SHV video on organic light-emitting diode displays. We also developed a driving method capable of temporal aperture control for each part of the panel in order to suppress motion blur on hold-type displays. We found that this method effectively improves the quality of moving images and demonstrated the feasibility of suppressing lifetime degradation due to a rise in instantaneous luminance. For the development of elemental technologies, we developed a technology for fabricating transistors that uses solution deposition and screen printing.

6.1 Advanced image sensors

6.1.1 Super-high-sensitivity image sensors

Low-voltage multiplier films for solid-state sensors

The sensitivity of solid-state image sensors decreases as the number of pixels and the frame rate increase. To overcome this problem, we have been developing photoconductive films (low-voltage multiplier films) that able to multiply the electric charge by applying a low voltage. In FY 2014, we further improved the sensitivity to visible light of chalcopyrite films and conducted imaging experiments using crystalline selenium films. These are two candidate materials for low-voltage multiplier films.

In FY 2013, we prototyped a p-n junction combining chalcopyrite film (p-type material) and tin-doped gallium oxide (n-type material). While it had increased the sensitivity to visible light, its quantum efficiency remained low (around 50%). As one of the causes was considered to be the low crystallinity of the chalcopyrite film, we newly introduced a multi-source deposition method to improve the crystallinity. This increased the quantum efficiency to 80%.

We stacked crystalline selenium films on an actual solid-state image sensor and conducted imaging experiments. The results showed fixed pattern noise for the entire screen although the resolution and response characteristics were acceptable (Figure 1(a)). We observed the film surface using a scanning electron microscope and found that the crystalline grain size and the
flatness of the surface were causing the noise. We demonstrated that reducing the grain size by thinning the layers of crystalline selenium films reduced the noise significantly (Figure 1(b)).

**Compact super-high-sensitivity imaging device for Hi-Vision**

We are developing field-emitter-array image sensors that combine field emitters that emit electrons when a voltage is applied to them with highly sensitive high-gain avalanche-rushing amorphous photoconductor (HARP) film (Figure 2). This effort is part of our work on compact, super-high-sensitivity Hi-Vision cameras for reporting at nighttime and in other low-light situations.

In FY 2013, we designed and prototyped a new electrostatic focusing field emitter to improve image quality and demonstrated that the field emitter can produce more than double the number of electrons than the previous method. In FY 2014, we developed an array with a large number of these emitters. They can efficiently get electrons from the cathode to the HARP film side, but if they are arranged in a pixel, the electron focusing effect is inversely proportional to the distance between field emitters (i.e., the pitch). We therefore sought the minimum pitch that can strike a balance between the necessary electron beam amount and the spatial extent by using electron beam trajectory analysis. We used the result to prototype an electrostatic focusing field emitter array incorporating a drive circuit with a pixel size of 11 µm x 11 µm (one-quarter the conventional size) that can be used for Hi-Vision. We also fabricated an image sensor using the array. This research was conducted in cooperation with the Advanced Industrial Science and Technology.

6.1.2 Organic image sensors

We are developing organic image sensors with an image quality comparable to that of three-chip color cameras for use in compact single-chip color cameras. These sensors consist of alternating layers of three different organic photoconductive films (organic films) sensitive to each of the three primary colors of light and transparent thin-film transistor (TFT) circuits for reading the signals from the photoconductive films on a glass substrate (Figure 1). To increase the resolution of these devices, the pixel pitch needs to be reduced and the defocus of each color in the optical images caused by the distance from each color’s organic film needs to be reduced. We prototyped a TFT readout circuit with a pixel pitch reduced to 50 µm, half that of conventional devices, and thinned the interlayer insulators.

We succeeded in nanofabricating a transparent amorphous In-Ga-Zn-O (IGZO) TFT by optimizing the etching conditions for fabricating the TFT. We also achieved a more than one-digit higher on-off ratio at 150°C, which is lower than the upper temperature limit for organic films, by using ozone annealing. For a thinner interlayer insulator, we formed silicon nitride film using a solution deposition buffer layer and plasma chemical vapor deposition. This enabled us to prototype a three-tiered structure of the three organic films with a total thickness of 5.8 µm without damaging the organic films (Figure 2). We thus showed the feasibility of a high-resolution organic image sensor.

The research on organic photoconductive films and on TFT circuits were conducted in cooperation with Saitama University.
6. Devices and materials for next-generation broadcasting

and the Kochi University of Technology, respectively.

[References]
(1) H. Seo, T. Sakai, H. Ohtake and M. Furuta: “Stacked Organic Photo-

6.1.3 3D-structured imaging devices

We are researching imaging devices with a 3D structure that can process signals from pixels in parallel as a way of improving the resolution and increasing the frame rate. These devices have stacked signal processing circuits for each pixel directly beneath the photovoltaic conversion element. This enables the signals from all pixels to be read in parallel so that a higher frame rate can be maintained even if the pixel count increases compared to common imaging devices with a 2D structure (Figure 1).

In FY 2013, we demonstrated the basic operating principle of 3D-structured imaging devices capable of converting the incident light intensity into pulse signals and outputting them in the depth direction of the device, but there remained the need to improve the sensitivity and reduce the dark current. In FY 2014, we enabled the device to capture moving images by arranging pixels in an array and investigated ways to improve the sensitivity and reduce the dark current.

To improve the sensitivity, we thickened the photodiode for the photovoltaic conversion element to increase the absorption of light and incorporated a structure to amplify the voltage generated by photovoltaic conversion to increase the output voltage of the photodiode. We also developed a signal processing circuit that can convert the output voltage of the photodiode into digital signals with higher precision. We demonstrated that dark current can be reduced by controlling diffusion of impurities into the photodiode. The development of these technologies shows the feasibility of constructing 3D-structured imaging devices with a practical level of sensitivity.

This research was conducted in cooperation with the University of Tokyo.

[References]

6.2 Advanced storage technology

6.2.1 Magnetic recording devices utilizing magnetic nano-domains

With the goal of realizing a high-speed magnetic recording device with no moving parts, we are developing recording devices that utilize the motion of nano-sized magnetic domains in magnetic nanowires. We previously developed a technology for using pulse currents to drive the magnetic nano-domains in magnetic nanowires and detecting the magnetization status for reproduction. In 2014, we developed a recording technology for forming new magnetic nano-domains and demonstrated the basic operating principle of magnetic recording devices utilizing magnetic nano-domains (Figure 1).

To verify the recording, motion, and reproduction of current-driven magnetic domains as a series of operations on a single sample, we redesigned the element arrangement and electrode structure and thereby developed a new way of fabricating magnetic nanowires. The conventional fabrication method, which molds a magnetic nanowire by cutting out the nanowire shape from the magnetic thin film deposited on the entire surface of a Si wafer substrate using the lift-off method, often forms burrs on the edge surfaces of the nanowire. As these burrs hinder current driving of magnetic domains, it was necessary to develop a process for forming magnetic nanowires free of burrs. We developed a lithography technology that

[References]
uses a bilayered resist structure consisting of an electron beam resist and a sacrifice layer resist to form a cutting mold template that has a unique, overhang-type sectional shape. This template enables the formation of ultra-flat nanowires without burns.

In order to form and detect the magnetic nano-domains in magnetic nanowire, we applied the magnetic domain scope with nano-order resolution (nano-MDS) method that we had developed in FY 2013 using a conventional magnetic recording head unit, in which a pair of write head and tunneling magnetic nanowires write head is closely-placed. Current-induced magnetic field can be generated from the write head and the strength of the applied field is changed by the distance between this write head and the specimen. By adjusting the structure of magnetic nanowires and their electrodes, the distance between the write head and the surface of magnetic nanowire can be reduced as close as 11 nm. Therefore, we can apply higher magnetic field to the magnetic nanowire and succeeded in forming stable magnetic domains in nanowire. The magnetic direction of each formed domain is easily evaluated using the output from the read-out head by nano-MDS method.

To clarify the phenomenon of current-driven magnetic domain motion, we developed a nano-magnetic simulation method incorporating the interaction between electrons and magnetic materials. This enabled us to investigate in detail the shape and size of the trap site necessary to stop and stabilize the magnetic domain motion and to clarify the relationships between trap size and shape and the trapping energy.

By combining this method with the technologies we previously developed for forming magnetic nano-domains, achieving high-speed driving, evaluating magnetic status, and fabricating ultra-flat magnetic nanowires, we made it possible to record multiple magnetic nano-domains with different magnetization directions in magnetic nanowires, drive them along the nanowires by using pulse currents, and then reproduce the magnetization information of the magnetic domain. Thus, the basic operation principle of our magnetic recording devices utilizing magnetic nano-domains has been demonstrated and verified experimentally.

[References]


6.2.2 Holographic memory

An archive system for recording and storing Super Hi-Vision video will need a very large capacity and high transfer rates. We have been researching high-speed and high-density holographic memory to meet these needs (1). In FY 2014, we worked on the development of a technology for increasing the data transfer rate for reproducing data from hologram.

The conventional method for reproducing data from holographic memory sequentially reproduces each data page by irradiating the hologram with one type of reference beam polarization. For higher-speed data reproduction, we devised a technology for reproducing two data pages simultaneously by irradiating the hologram with two types of reference beam polarization (Figure 1). We implemented two optical systems for use with holographic memory: a polarization division and angle control optical system for dividing the reference beam entering hologram into p- and s-polarization beams and controlling their incident angles and a polarization isolation optical system for isolating the reconstructed beams exiting the hologram into p- and s-polarization components and detecting each reproduced data item. We recorded angle-multiplexed holograms using these optical systems and verified the principle of dual-page reproduction. The results showed that the error rate of reproduced data was lower than practically allowable (3.0×10⁻⁵) for both the reproduction by p-polarization and by s-polarization, demonstrating the effectiveness of the dual-page reproduction technology we devised.

[References]


6.3 Next-generation display technologies

6.3.1 Multiple-division-scanning-drive-display

We are researching ways to display high-quality full-specification Super Hi-Vision video using an organic light-emitting diode (OLED) display. To improve the quality of moving images in particular, we had previously researched compartmental area scanning drive technology for displays as a means of achieving a higher frame rate. In FY 2014, we investigated a panel structure for enabling the creation of a multiple-division-scanning drive. We also proposed a new method for driving OLED displays and evaluated its performance through simulation experiments.

To divide an OLED display into multiple areas and drive them separately, we devised a new configuration for the lead wire and developed elemental technologies for forming electrodes. We also proposed a driving method capable of temporal aper-
6.3.2 Core technologies for flexible displays

We are aiming to develop ultra-flexible, large-size flexible displays with low-cost solution-based technique. In FY 2014, we improved the performance of organic thin-film transistors (TFTs) with a flexible element structure and developed a panel fabrication technology based on printing technologies.

Organic TFTs using soluble small molecular-based semiconductor materials have large variation in the crystalline size within the semiconductor film, making it difficult to obtain uniform performance on the entire substrate. To address this problem, we developed a film deposition method for controlling the crystalline size of precipitated semiconductor film by controlling the evaporation speed and drying direction of the solution. This led to the successful development of a uniform crystalline film with a crystalline size of several hundred micrometers and enabled us to fabricate a TFT array with high mobility, comparable to that of amorphous silicon TFTs.

Development of the panel fabrication technology included work on improving the TFT characteristics of flexible displays fabricated using a screen-printing method. Conductive materials in the conductive ink typically spread into the insulating layer at the time of electrode printing, degrading insulating performance of TFT. To deal with this problem, we adjusted the composition of the conductive ink and drying conditions during printing. This suppressed the deterioration and reduced the off-current value of the TFTs significantly. We also reduced the contact resistance between S/D electrodes and organic semiconductor by surface treatment and nanofabrication of the electrodes, which greatly increased the on-current value.

We prototyped a 64×64 pixel panel and demonstrated acceptable operation of TFTs fabricated using these printing technologies (Figure 1).

[References]