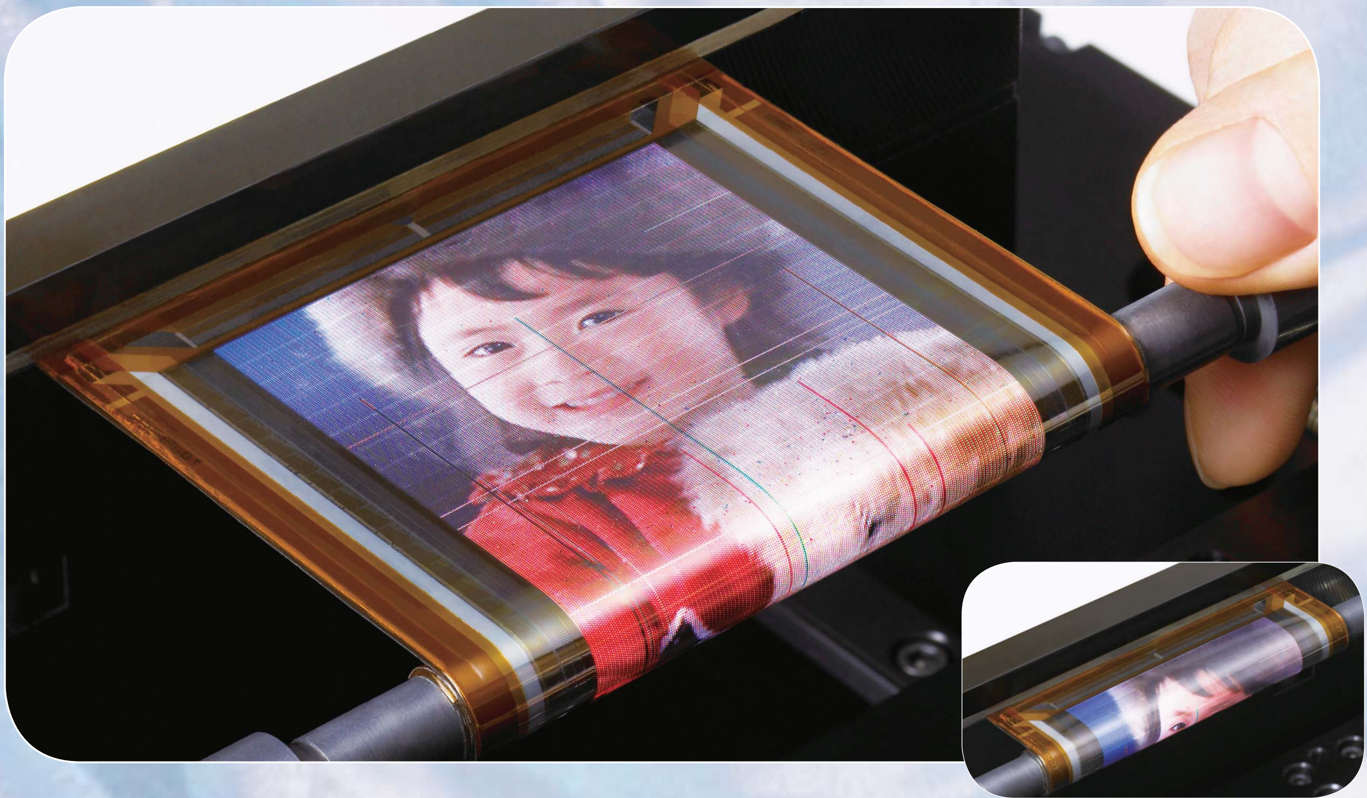
SIDE VIEW

Improved performance OTFTs achieved with unique organic semiconductor materials

OTFT-Driven OLED Display that can be Rolled up onto a Pen



For the first time[*3] in the world, Sony has succeeded in creating an OLED display that can continue to display video while being rolled and unrolled repeatedly onto a cylinder with a radius of curvature of 4 mm.

*: Sony is broadcasting from our web site a video of this display playing a video while being rolled up. http://www.sony.net/SonyInfo/News/Press/201005/10-070E/index.html

A display that rolls up like paper.
We have finally arrived in an age where, the flexible display or rollable display, which has long been discussed as a dream of the future, can be seen in front of our own eyes.
Sony has now developed a 0.08 mm thick, 121 ppi resolution 4.1-inch OTFT[*1]-driven full-color OLED display that is so extremely flexible that it can be rolled onto a thin tube.
In May at this year's SID (Society for Information Display) 2010 conference held in Seattle, Washington, Sony announced this display and received an enormous response as people crowded around to see the operational demonstration Sony exhibited.
This display was developed by combining a wide range of new technologies, including OTFTs with an increased drive performance by a factor of eight[*2] over earlier devices.
These OTFTs are made with Sony developed original organic semiconductor material, which is a "PXX derivative".
This article presents an overview of these technologies and a message from the developers.

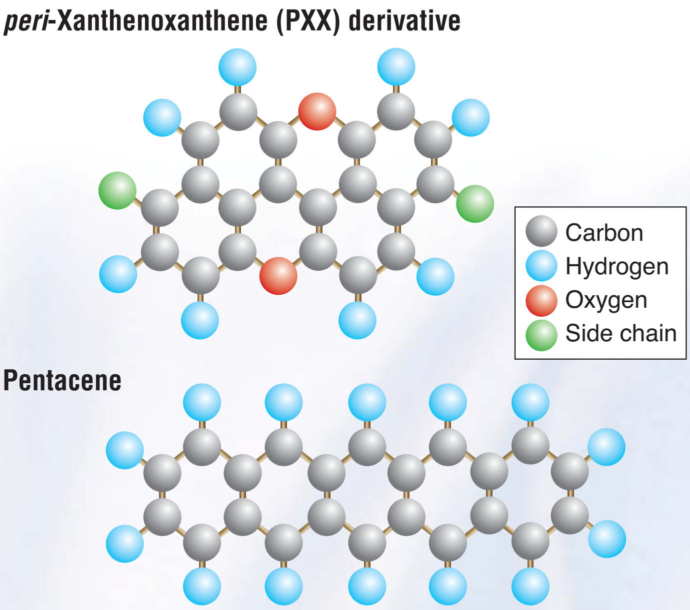
■Specifications of the Prototyped OTFT

Organic semiconductor material	*peri*-Xanthenoxanthene (PXX) derivative
Hole mobility	0.4 cm^2/Vs
Current on/off ratio	10^6
Channel length	5 µm
Threshold voltage	–5 V

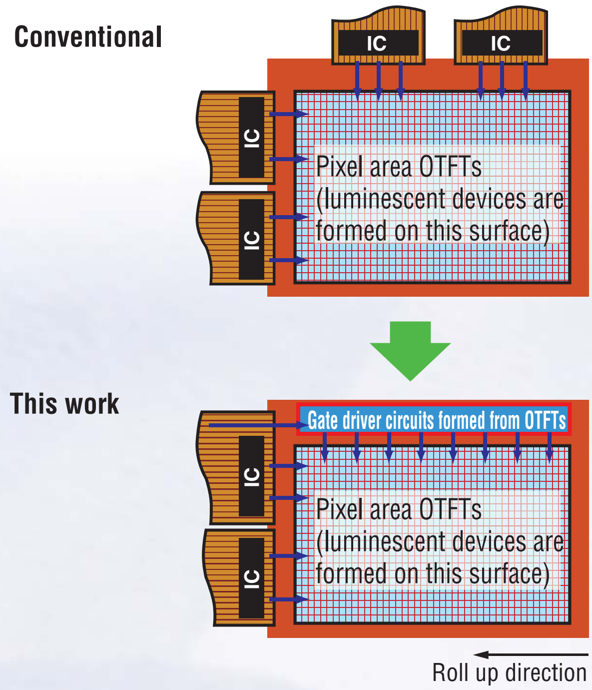
■Specifications of the Rollable OTFT-driven OLED Display

Panel size	4.1-inch wide
Number of pixels	432 × 240 × RGB pixels
Pixel size	210 µm × 210 µm
Resolution	121 ppi (pixels per inch)
Number of colors	16,777,216 colors
Peak luminance	> 100 cd/m^2
Contrast ratio	> 1000 : 1
Minimum bending radius	4 mm
Drive type	2T-1C voltage drive using OTFTs
Panel thickness	0.08 mm

*1: OTFT: Organic Thin-Film Transistor
*2: Internal comparison between OTFTs with pentacene ($C_{22}H_{14}$) and OTFT with a "PXX derivative".
*3: This is the world's first OTFT-driven rollable OLED display, as of May 2010. According to Sony survey.
*4: This is the world's highest resolution OTFT-driven rollable OLED display, as of May 2010. According to Sony survey.



■ The Sony-developed organic semiconductor material, a *peri*-Xanthenoxanthene (PXX) derivative



■Gate driver circuit formed from flexible OTFTs

Organic materials, such as plastics, are thought to have difficulty conducting electricity. There are, however, organic materials that conduct electricity and there are even some that have semiconducting properties. Recently, there has been extensive research carried out worldwide on flexible thin-film transistors that use organic materials with semiconducting properties. Such transistors are refered to organic thin-film transistors (OTFTs). In an OTFT, the electricity (current) flowing in an organic semiconductor material is controlled by external signals. Thus the organic semiconductor material, which determines the performance of the OTFT, becomes one of the main points of this work.

Sony has been engaged in research and development on OTFTs with implementation of flexible displays as the target.

In the background to the creation of this newly-developed rollable display was the fact that Sony was able to improve the performance of OTFTs by using a unique organic semiconductor material developed by Sony.

New Technologies/ New Developments (1)

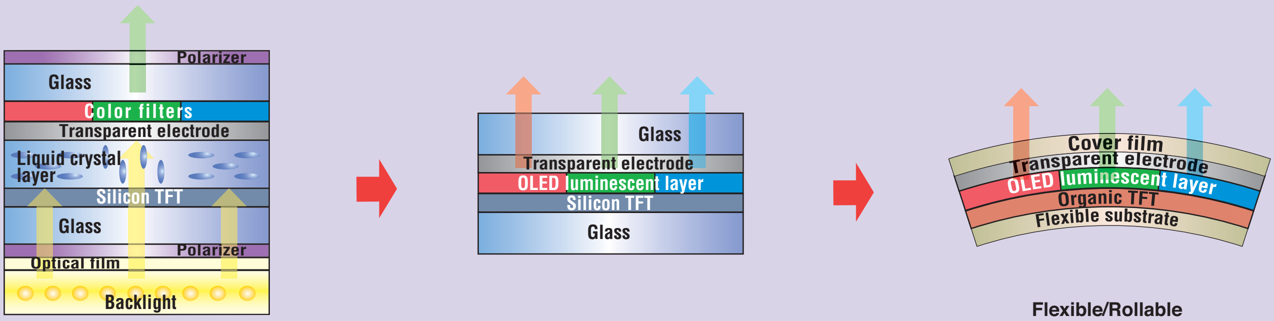
High-performance OTFTs using a unique Sony-developed "PXX derivative" organic semiconductor material that features superlative conductivity and stability

Sony has developed an OTFT that uses a unique Sony-developed *peri*-Xanthenoxanthene (PXX) derivative organic semiconductor material that can make TFTs with high carrier mobility and has a stable molecular structure that is not easily degraded by oxygen, water, light, or heat. This OTFT achieves eight times*2 the drive performance of transistors implemented using the conventional organic semiconductor material pentacene. It is the pixel transistor that controls the OLED emission at each pixel, and if this transistor is made smaller, the pixel itself can be made even smaller. In this display, the increased drive performance of the OTFT, allows the size of the pixel transistor to be made even smaller, and it achieves the world's highest*4 resolution of 121 ppi in an rollable OLED display driven by OTFTs (OTFT-OLED display).

New Technologies/ New Developments (2)

A flexible gate driver circuit is integrated using OTFTs in place of the conventional hard IC chips that were seen as an obstacle to achieving a rollable display

Voltage pulses to control the pixel circuits are supplied by an external circuit. Conventionally, this circuit is formed with a rigid silicon IC, and such ICs are mounted on the panel. In contrast, in the current development effort, we were able to form this gate driver circuit from flexible OTFTs due to the improvement in performance achieved in these OTFTs. This is the first time in the world*3 that any company has succeeded in forming an OTFT-OLED display using gate drive circuits formed from OTFTs. By eliminating the hard IC chips that prevented from bending, it is now possible for the display to be rolled.



LCD Display

OLED Display

Flexible/Rollable OLED Display

LCD displays create images with light that passes through color filters. The light from the backlight is controlled by opening and closing LCD shutters on each pixel that are controlled by TFTs.

Since OLED displays directly emit light with TFT-controlled luminescent elements in the OLED light-emitting layer that correspond to the red, green, and blue pixels, no backlight is required and they can be made much thinner.

In conventional LCD displays and OLED displays, the TFTs that control whether or not each pixel is turned on, are formed from inorganic silicon materials, such as amorphous silicon or polycrystalline silicon. Glass must be used for the substrate material, since the manufacturing processes for these silicon-based TFTs require temperatures of 350 °C or higher. Although the materials used to form LCDs and OLED devices themselves are soft and pliable, it has been difficult to create flexible displays due to the hardness of the TFT substrate. In contrast, OTFTs can be manufactured by comparatively low-temperature (room temperature to around 200 °C) processes, and can be formed directly on flexible substrates such as plastics. This results in a flexible display. When glass is used as the substrate, a certain thickness is required to prevent breakage, but use of a flexible substrate would allow the creation of thinner displays, and these could provide the added value of extreme light weight and not breaking easily.

New Technologies/ New Developments [3]

Flexibility assured by forming all the insulating layers in the OTFT and OLED integrated circuits from organic materials

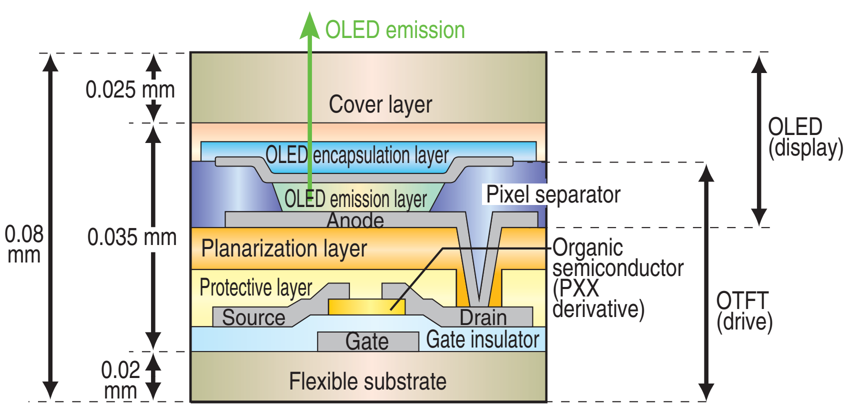
By forming all the insulating layers of the OTFT and OLED integrated circuits from flexible organic materials, Sony was able to assure high flexibility. The organic materials used in the insulating layers were formed with a coating or a painting process, which is possible because these organic materials are soluble.

[1] + [2] + [3] = Rollable

Achieving video playback while rolling the display screen to a 4 mm radius of curvature

By combining the technologies described in items [1] through [3] above, Sony created a display that can playback video while being rolled to a 4 mm radius of curvature. In our test development data (at the time of the SID publication) we verified that there was no clear degradation in display quality even after 1000 cycles of the roll/unroll test.

Since it is easy to dissolve organic materials in a solvent and create an ink solution, it is hoped that in the future it will be possible to create such displays using printing processes, and research and development efforts on this are underway around the world. If this were achieved, unlike conventional integration processes that use the current inorganic silicon-based materials and that require high temperatures and vacuum equipment, it would be possible to produce devices at low temperatures, under ambient conditions, using fewer process steps and with minimal material waste, and it is hoped that in the future devices could be produced with low energy consumption and with low environmental impact. While it will be difficult to apply this to advanced LSIs, this technology will be highly applicable to the TFTs of larger display sizes and flexible displays. We hope and expect that this success will lead to electronic equipment that is thinner, lighter, more resistant to mechanical shock, and can be collapsed for easier storage. Moving forward, Sony will continue to work on research and development to improve the performance and reliability of organic semiconductors and to achieve coating and printing processes for mass production of these devices.



■OTFT and OLED devices are integrated on an ultrathin 0.02 mm flexible substrate

Materials Technology and Device Technology. Our Strength Lies in How Close Together they are at Sony.

The development of organic semiconductor materials that can withstand the critical stares of the other members of the team and device development that strives to take advantage of those materials' properties. A soft and rollable display was created by a solid and uncompromising collaboration.

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If the challenge is not unreasonable in principle...

— Sony has already, in 2007, announced a flexible display.

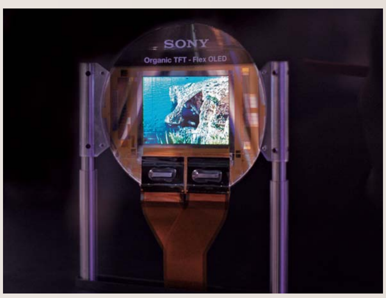
Nomoto: That was the prototype we developed first. It was a 2.5-inch 120 × 160 pixel (80 ppi resolution) display, and was the world's first flexible full-color OLED display driven by OTFTs (OTFT-OLED display). It created quite a response when we published the news release. It was introduced by Japanese TV programs and it was selected for Time Magazine's "The Best Inventions of 2007". This time, we are getting much less media exposure, but when we presented on the Sony web site a video of this OTFT-OLED display playing back a video while being rolled up and then unrolled repeatedly, that page quickly became the most accessed Sony video press news page by far.

— When you presented your work at the 2009 International CES (International Consumer Electronics Show) the radius of curvature was 25 mm, and it was still only a bendable display. I understand that you set yourselves the goal of reducing the radius by an order of magnitude. In fact, a year later, you have achieved a radius of curvature of 4 mm, and this device can truly be called rollable.

Nomoto: The order of magnitude goal applied not only to the radius of curvature, but also to the panel thickness (from 0.2 mm to 0.08 mm), the transistor drive performance, and other aspects as well.

— What was your reaction when you heard that target?

Yagi: This was the subject of much discussion among the team members. Our main question was whether or not the goal was in principle unreasonable. If the target isn't impossible, let's do it, was our attitude. We are fond of processes of the sort in which you have a state where you can just barely touch something by jumping and you improve to the state where you can grasp it reliably.



The 2.5-inch flexible OLED display exhibited at International CES in January 2009

Nomoto: We also had the PSP®* size as our target. And the display we developed has specifications that are very close to PSP®. To have an even greater impact, we aimed at a level that would succeed as an actual product. At that time, however, a resolution of 121 ppi in an OTFT-OLED display was a specification that was impossible for everyone working in this area worldwide.

Yagi: One problem was that when multiple layers were stacked on a flexible substrate, since stretching and shrinking could occur, if the pattern was too fine it would become impossible to align the features in different layers. Our arguments as to whether or not this would be possible almost turned into fights.

Nomoto: While this situation was continuing, the engineer in charge of circuit design suggested mounting the gate driver circuits onto the panel itself.

Yagi: Yes. That was suggested. (Laughs.)

Nomoto: That was the team member who wanted to name this project "Escargot". I think he was a gourmet. Anyway, to achieve a resolution of 121 ppi, we needed OTFTs with a correspondingly high drive performance. In principle, if the pixels functioned, then the drivers should be able to as well.

Kobayashi: This was difficult from a materials standpoint.

Nomoto: To achieve that level, we had no choice but to give up on the "pentacene" organic semiconductor material that had been used up to that time. So we said to Dr. Kobayashi "you can do it." (Laughs.)

*: PSP®: "PlayStation Portable" is a registered trademark of Sony Computer Entertainment, Inc.

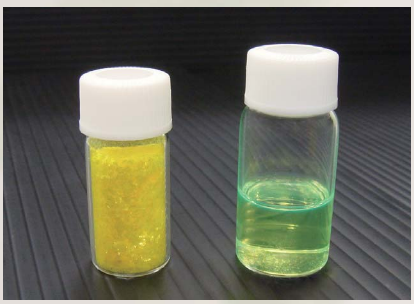
The device properties determine whether or not we will be able to use the benzene rings.

— How much time did you spend developing the new material, the "PXX derivative"?

Kobayashi: Getting it to the point that everyone could use it took 5 years. The most important aspect was stability. In the basic research phase, if you make 100 devices and one produces good data, you have succeeded. But if you try to make actually transistors with that material, when you make 100 devices, all 100 must have the same characteristics.

Nomoto: Not only that, but just because you can make transistors doesn't mean you can rest on your laurels. You have to form a protective layer, the pixel electrodes, and the emission layer on top of the transistor. They will be subject to heat and various solvents.

Kobayashi: The greatest feature of this new material is, perhaps, that it can survive these stresses and after making it through, continue to exhibit its abilities. If you look at the molecular structure, it is just a sequence of hexagonal benzene rings, but properties are radically different from those of previous organic semiconductor materials.



The "PXX derivative" high-performance organic semiconductor material developed by Sony. On the left is the powder form used in the development effort described here. On the right is an ink-solution with a "PXX derivative" for use in future printing processes.

— If you look at this structural formula, can you predict, at least roughly, what sorts of properties it will have?

Kobayashi: We can, of course, predict what the properties will be, but it is extremely difficult to get the right answer. The chemical properties of the molecule itself, and the properties that arise when molecules are assembled into a film, are different questions.

Nomoto: Although we also use organic semiconductor materials in the OLED emission layer, those are amorphous (non-crystalline) materials. They are arranged randomly in space and each emits light individually. In contrast, we use polycrystalline organic semiconductor materials in organic transistors. Thus we sometimes refer to such materials as "poly-organics", and how perfectly the molecules can be arranged is critical for such materials' performance.

Kobayashi: The properties change radically depending on how neighboring molecules interact with each other. The way these molecules order themselves cannot be simulated even with the most advanced simulation technologies.

Nomoto: In general, device developers are not very familiar with these benzene rings. The developers on the team both learned a lot from, and had to teach a lot to, Dr. Kobayashi, who is really good at working with benzene rings. We had many discussions that covered multiple fields of study. Our greatest strength was that the materials developers and the device developers worked together as a single team. This is why we were able to develop such a device ahead of the other companies who are working in this area.

From materials development to device development: passing on hopes and responsibility.

— What sort of interactions were there between the materials developers and the device developers?

Kobayashi: I'd take some data to Dr. Yagi and ask "How about this?", and he'd say "That's terrible!" without even the slightest hesitation. So I'd say "OK, I'll be back".

Yagi: Hey, you're making me sound cold and cruel, (laughs) but seriously, I thought that we worked together well as professionals with an appropriate level of tension. Previously, our device developers had thoroughly analyzed a variety of materials that Dr. Kobayashi had synthesized for us. In those efforts, all we cared about was the results. There were several cases where we had to reject an otherwise interesting material for technological reasons. At those times, our "report cards" were critical to the point that I felt sorry for the recipient.

Nomoto: We would rate the material aspects on a scale of A to F. If just one was a "D", the material was rejected even if all the other scores were "A".

Kobayashi: I was really nervous when I brought this material over for evaluation. When my children get a bit older, I suppose that is how I'll feel when I see their report cards.

Yagi: After that we tested improved versions of materials time and time again. The result of all these tests was that just one remained: the "PXX derivative" we used in this project. Having come to this point, we could no longer blame the material and now it was our turn to sweat bullets. Still, even if it was nerve-wracking, it was fun.

Nomoto: That is because variations in material properties can be suppressed by the process technologies.

Kobayashi: While I watched as engineers from specialties other than mine put together devices using my materials, it was an experience of continual surprise, worry, and new discoveries. It was stimulating in a variety of ways. Oh, yes. That reminds me: Dr. Yagi and I joined Sony the same year.

Nomoto: Oh, so you guys are the same year? That makes things easier. Here in Japan, it can get complicated when there is a difference in seniority, no matter how slight. (Laughs.)

Yagi: That's because neither of us has to be overly considerate of the other.

Kobayashi: We approached our meetings with the attitude that if the other guy wanted to make progress, I'd do my best. Otherwise, forget it. Since we had experienced a lot of difficulties, I almost cried the first time we managed to get it to display an image. The materials I had created holding the flasks myself were driving this display.

Yagi: I, on the other hand, only experienced a brief flash of joy at that. I was soon worrying about how to make the display rollable and what to investigate next.

Kobayashi: But I didn't get to rest, either. As soon as we had the device displaying images, the next problem was waiting; namely the printing process. The project required that the material be made more ink like.

Nomoto: These two technologies, materials and devices, are two equal pillars that support this project. While it appears that there are still people who doubt that organic materials can be used in these sorts of devices, we have the strong impression that they definitely can, both in the devices themselves and in a printing process. We will be doing our best to create products that give Sony an overwhelming lead in this area; you can count on it.

"Our end target is a rollable large-screen TV. The time will come when the very idea that an enormous black box (TV) was ever placed in rooms will seem strange." (Nomoto)