Organic Transistor

A new generation of transistors

Research and Development on Organic Transistors has Progressed Even Further

The mechanism for electrical conduction has been elucidated and carrier mobility improved

The materials from which semiconductor devices are made are the inorganic semiconductors silicon and germanium. This "well-known truth", which remained valid since the transistor was invented in 1947, has been turned on its head by the appearance of the organic transistor. Organic transistors have a charismatic potential and hold the promise of products such as electronic circuits printed on a sheet of plastic and enormous displays as light and flexible as paper. However, there are still many technological problems to be solved. Sony has resolved one of those problems, bringing us one step closer to the realization of these dreams.

■ Organic Transistor Features ---a comparison with silicon transistors

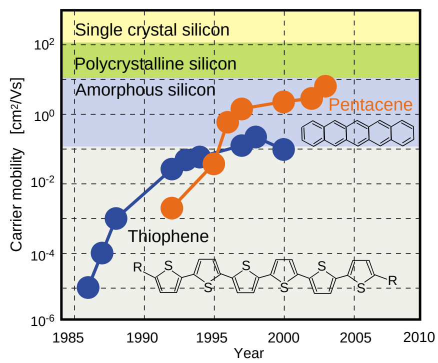
Advantages

- Flexible
- Able to withstand mechanical shock
- Light weight
- Suited for use with plastic substrates (low-temperature process)
- Support applications with larger areas
- Reduced costs are possible due to the use of printing and other technologies.
- Increasing possibilities due to the diversity of organic molecules.

Problems

- The technology is still immature
- Performance is insufficient (mobility)
- Reliability is unknown

■ Progress in Organic Transistor Performance



While research began in the 1980s, performance improved dramatically during the 1990s. Devices using pentacene as the organic material achieve carrier mobility equivalent to that of amorphous silicon.

Gazing at the Far Side of Silicon

Research using organic materials (compounds based on carbon) as the material for transistors began in 1984. Although the research in Japan led the world at that time, the carrier mobility of those materials was nowhere near that of even amorphous silicon and the technology was far from practical.

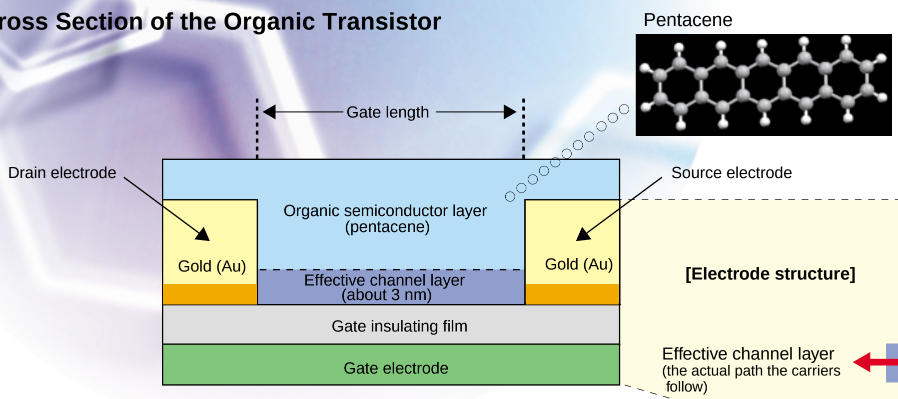
The performance of organic transistors improved greatly at the start of the 1990s. Then in 1997, instead of thiophene, the original organic material used in this research, pentacene was used, and a carrier mobility of the order of 1 cm^2/Vs, which is comparable to that of amorphous silicon, was reported. Additionally, Bell Laboratories caused an uproar by announcing an organic transistor based on a self-assembled monolayer film, an event that became the catalyst that created a worldwide boom. In recent years, sessions related to organic transistors at international conferences have become standing room only events.

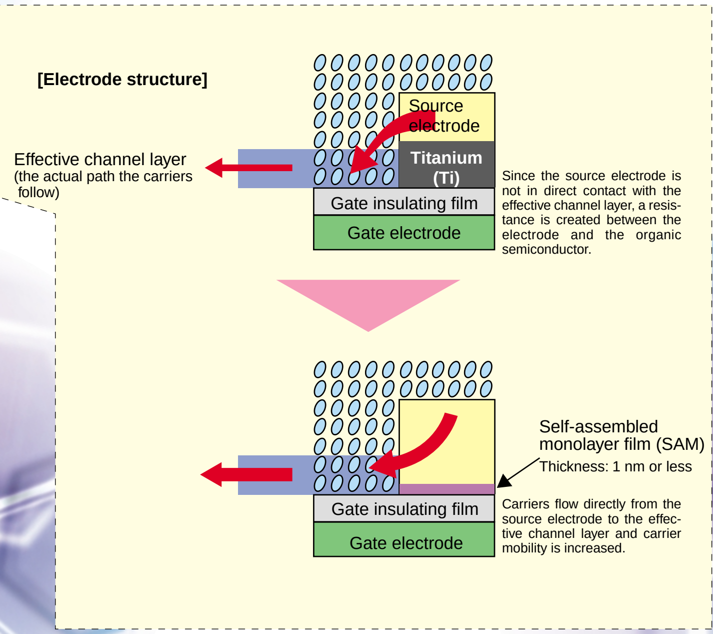
There are Still Mysteries, and Dreams are Just Beginning

Even if it were the case that characteristics similar to amorphous silicon appeared at the research and development phase, that in itself would not be enough to cause a shift to a new generation. There were still many issues to overcome at the basic research stage to meet the performance requirements for transistors. In the first place, the operating mechanisms of the organic transistor have not yet been fully understood. Although operation of the organic transistor is in principle the same as that of silicon field-effect transistor (FET), how carriers flow in organic materials is not adequately understood.

However, Sony's Fusion Domain Laboratory, Materials Laboratories has now explicated one part of those principles, namely the path that carriers pass through. Before we discuss into that explanation, we would first like to summarize why researchers around the world are taking pains to make organic transistors practical.

■ Cross Section of the Organic Transistor





The electrical conductivity is increased by adopting not the titanium used previously but a self-assembled monolayer film (SAM) as the adhesive material between the source electrode/drain electrode and the gate insulating film. This overcomes the earlier problem of the carrier mobility falling as the transistor size is reduced (the gate length is reduced).

Changing the Manufacturing Process and the Semiconductor Concept

Should we use silicon (inorganic) or should we use organic materials? It turns out that the largest difference between them is in the manufacturing processes.

Transistors using silicon require a complicated and high precision manufacturing process that creates electronic circuits by starting with a single-crystal silicon substrate and applying a variety of processes such as lithography, the addition of impurities, deposition, and etching. Large scale and expensive equipments, such as clean rooms and vacuum systems, is required.

In contrast, with organic transistors, one can take advantage of the features of organic materials and, by dissolving them in a solvent, use printing technologies such as rotary press or inkjet printing to create circuits simply. Since these are low-temperature processes, they have excellent compatibility with plastic substrates. It is possible to “print” pixels and transistors on a thin plastic sheet and to manufacture large-screen displays that are light and flexible.

Furthermore, since the flexibility in formation is increased, for example, one can print circuits on curved surfaces, applications such as artificial skin for robots have been announced.

Sony’s Viewpoint (1) The Discovery of a Detour

The relationship between device size and carrier mobility remained a major obstacle to realizing the rich possibilities inherent in the organic transistor.

In field-effect transistors, response becomes faster and higher integration densities become possible the smaller the size of the device, that is, the shorter the path (gate length) through which carriers flow in the organic semiconductor layer from the source electrode to the drain electrode. (See the figure above.)

However in organic transistors, the carrier mobility is reduced greatly as this gate length becomes shorter. This is one of the main factors preventing the practical use of organic transistors.

Why does the carrier mobility fall? Sony has defined that the cause is that since loss (contact resistance) occurs in the current flow from the source electrode to the semiconductor layer, that loss becomes relatively larger as the gate length is reduced. Sony analyzed the conduction mechanism in that section and showed that the path that the carriers pass through (the effective channel layer) is a thin layer (about 3 nm) consisting of just a few molecules. Previously, carriers did not flow smoothly, since the source electrode and the effective channel layer were not actually in contact due to the thickness of the titanium or other material used to bond the source electrode to the gate insulating film.

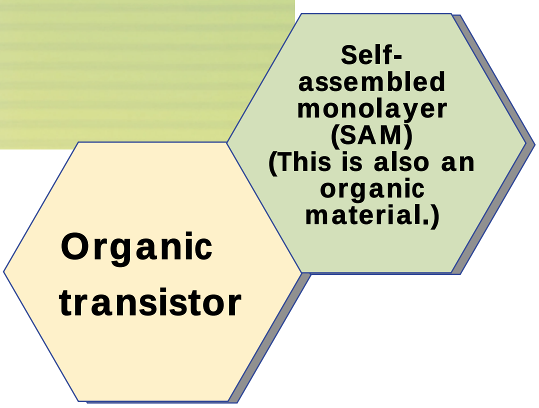
This was like coming across a detour with poor paving at some point on a superhighway.

Sony’s Viewpoint (2) Using Self Assembly

Based on this knowledge, Sony thought that carrier flow could be made more efficient by reducing the thickness of the bonding layer and increasing the area of contact between the source electrode and the organic semiconductor layer. What Sony used instead of titanium was a self-assembled monolayer (SAM) of organic material. This is a film that makes use of the property that, when certain processing is applied to the substrate, organic molecules attach themselves to the substrate in individual molecule units due to a chemical reaction. This film has a thickness of under 1 nm.

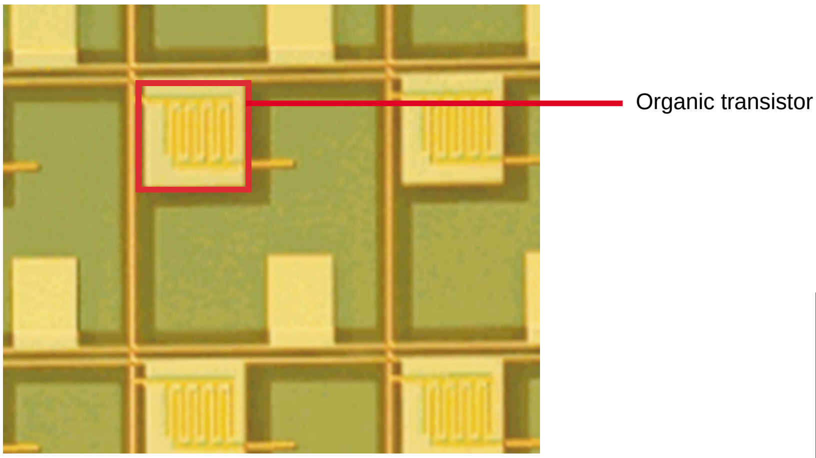
By sandwiching this film between the source electrode and the gate insulating film, Sony reduced the contact resistance and achieved transistor performance in which carrier mobility does not fall when the gate length is reduced. (Carrier mobility was increased by a factor of more than 50 over previous Sony devices.)

Furthermore, Sony succeeded in using



■ Photomicrograph of an LCD Display Driven by Organic Transistors

— Announced in February this year at ISSCC (IEEE International Solid-State Circuits Conference)



*: This time, the organic transistors were fabricated not by painting but by vapor deposition.

organic transistors that adopt this technology for pixel switching and operating a 2.5-inch monochrome transmissive TN LCD display (160 × 120 pixels). Sony announced these results at the ISSCC 2004 (IEEE International Solid-State Circuits Conference) held in San Francisco in February this year.

Although this work is still at the research stage, Sony received a strong positive response to this announcement that showed, in a clearly visible manner, that practical use of organic transistors is actually possible. Questions continued long after the session had ended.

A Performance of the prototype organic transistor (discrete device)

Carrier mobility	1.1cm^2/Vs
On/off ratio	10^6
S value	0.3 V/decade
Gate length/gate width	100 μm/200 μm
Organic material used in the semiconductor layer	Pentacene ($C_{22}H_{14}$)

Specifications of the organic transistor drive monochrome transmissive TN LCD display (prototype)

Screen size	2.5 inch
Pixel count	19,200 pixels
Pixel size	320 μm
Aperture ratio	73 %
Organic TFT gate length	5 μm
Gate width	400 μm

From the Laboratory

Devices to which we can entrust our dreams

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Printing out IC Tags!?

Kasahara: While organic transistors have many advantages, when seen from current trends, the ability to increase the area is extremely important. Why is it possible to increase the area? Because they can be manufactured by dissolving the materials and painting the solutions onto a substrate, that is, they can be manufactured using printing technologies.
Wada: The culture is completely different from that of silicon transistors. Because the image is one of devices in a sheet form emerging from printing equipment.
Kasahara: Even with printing technologies, fine fabrication with feature sizes on the order of 1 µm is still possible, and these technologies are expected to improve in the future.
Wada:For applications in which faster speeds are not that important, I expect that it will be possible to print devices using inkjet printers.
Kasahara: In some cases, one may be able to create one's own circuits using your home personal computer and home printer.
Wada: One application that is talked about a lot is the wireless IC tag. Currently, the costs for mounting this functionality on a chip are excessive, but if the circuit could be printed, IC tags could be created for under a penny each.
Kasahara: Each shop could create their own IC tags and apply a sticker to each product. I suspect that this will become possible.

The Fascination of Organic Materials

Kasahara: The chemical reactions that organic materials can take part in are extremely diverse, and that makes them fascinating. The SAM technology discussed in this article is one such reaction. In that reaction, which is a unique phenomenon, if an appropriate “partner” is provided, the organic material will attach to that partner one molecule at a time and form a thin film.
Wada: It's also possible to overlay molecules on molecules just as you want. Since the structures of inorganic materials are determined strictly, there is not as much flexibility when working with them.
Kasahara: The organic material known as pentacene is also extremely difficult to dissolve in a solvent, and cannot be used for printing without modification. However, if some slight modifications are made in the side chains, materials that cannot be dissolved become soluble. Not only is the manufacturing process different, this technology has the possibility of being deployed in a wide range of applications by using a variety of organic molecules.

Fusion and Mutation

Kasahara: In the current semiconductor world, progress cannot be made focusing solely on electrical engineering. If one is dealing with molecular electronics, one must find the seeds for new ideas from the field of biology, and then must make an even more thorough analysis from the standpoint of the physics of the system. This means that researchers from differing fields must eat at the same table. Which is why the “Fusion Domain Laboratory” was organized. The actual structure of the group is currently an equal number of electrical engineers, physicists, and chemists.
Wada: When someone such as myself, who comes from an electronic device background, finds themselves having difficulties, a chemist will often advise to try some specific material. Inversely, when they say “we can’t seem to get the desired performance from this”, we can take advantage of our knowledge and sense from the semiconductor area. Thus we can help each other make progress.
Kasahara: This expands one’s point of view. Things that one previously couldn’t see become clearly visible. Although, in general it has mostly been chemists who have been involved with organic semiconductors, with this research project at Sony, physicists and engineers have participated in the discussions. I think this is a major factor that enabled us to produce results before other companies in this area.
Wada: At any rate, this is new and exciting. In the chemistry and semiconductor worlds, the ambience at the conferences is completely different. Even the units used are different.
Kasahara: Chemistry has the weight of a continuous history going back to the days of alchemy, whereas the frankness of a youngster is taken as being only natural in the semiconductor world. I think that this fusion is evolution itself. It is because these differing genes meet that mutations occur and evolution occurs. I think that new technologies will most certainly arise from this sort of place.

Will Shockley be Surprised Twice?

Kasahara: When I’ve finished giving a presentation, I’m often asked "When will this be ready for practical application?". But this work is basic research, and will not soon result in actual products. Performance must be improved, and reliability testing is required. And if we get to the point where this technology is used in a manufacturing line, it will most likely run into unexpected difficulties there. I hope that you will follow this technology, as a device worthy of our dreams, with hopes for the future over many years.
Wada: Although still a dream, I believe that organic transistors will be used in a range of applications not possible for silicon transistors. I also expect that new worlds of electronics can be created by collaboration with silicon transistors.
Kasahara: In an article introducing our work in a certain magazine, the author was kind enough to write “Shockley, Bardeen, and Brattain would be surprised.” Ignoring the question of whether or not they would really be surprised at this work, I suspect that they themselves, the inventors of the transistor, did not foresee anything like today’s LSI age. I don’t think that it is meaningful to argue whether or not organic transistors will, given their current performance level, advance in a similar manner and overtake the performance of silicon. That’s because this technology is still at the development stage of a grade school child. Now we must work to cultivate the possibilities of this technology and hope that finally a new world will open.