The middle way: combining molecular electronics with traditional silicon

Dr. Ryoma Hayakawa

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Dr. Ryoma Hayakawa is an independent scientist at Japan's International Center for Materials Nanoarchitectonics. Here he discusses his attempts to realise the next generation of computer architectures.

What inspires you to work in materials science?

Materials are the basis of all productions and the evolution in our current science and technology has been achieved by the enormous discoveries of novel materials. The silicon industry now faces a major turning point owing to the critical limit imposed by increasing large-scale integration and growing power consumption.

The improvement in performance cannot be achieved by simple miniaturisation of transistors anymore. Therefore, exploring new materials is urgently required in current complementary metal-oxide semiconductor (CMOS) technology. Materials science and engineering is really essential to open up a new era in future CMOS architectures.

Why did you decide to combine traditional CMOS architectures with emerging molecular structures?

I have worked in the fields of both silicon and molecular electronics. Current CMOS technology faces a major turning point and development of new devices with novel principles is urgently required.

On the other hand, single molecular devices, which utilize single molecules as an electronic component in transistors and memories, are expected to be a promising candidate further in the future.

The development of molecular devices is, however, still at the basic research stage and practical applications remain a long way off. The main obstacle is the lack of effective device structures for molecular devices.

Hence, our approach of integrating attractive molecular functions into Si-based devices meets the requirements of both fields.

You describe the device you are trying to make as multifunctional. Why is that?

Improvement of transistor performances cannot be achieved only by miniaturization. Integration of new functionalities like multi-valued operation and integration of memory and photonic functions is necessary to push ahead with the improvement of device performances beyond the limitation in downscaling.

For this reason, we opted to use organic molecules as quantum dots to integrate attractive multifunction into future CMOS devices. The unique features of organic molecules including size uniformity, excellent controllability in energy levels, photonic functions and molecular spin manipulation, have the potential to integrate new functions into CMOS devices.

Manipulation of quantum transport with a few carriers contributes to a considerable reduction in power consumption and high-speed operation. The multi-valued operation, which is controllable by molecular orbitals, also allows further large-scale integration of electronic circuits. Adoption of photochromic molecules and magnetic ones could enable integration of optical memory and spin memory functions.

Do you think photonic and quantum technology is the future of computing?

Optical manipulations of devices are critical elements in future CMOS technology. In our study, we used photochromic molecules as optically controllable quantum dots in a Si-based double tunnel junction.

The advantage is that the energy levels of the molecules can be varied reversibly by light irradiation with specific wave lengths and the change in molecular structure induced by light irradiation can be maintained. In other words, the device works as a non-volatile optical memory. Such optical functions will be very favourable in the future.

In addition, the development of quantum transport devices is required in future CMOS devices because the devices allow extremely low power consumptions due to only having

to manipulate a few carriers. They also permit multi-valued operations with discrete levels in a quantum dot. Furthermore, the unique features such as superior controllability in energy levels, as well as photonic and spin functions, make it possible to integrate novel functions into current Si devices.

Japan is renowned for its expertise in electronics. Do you believe the country will maintain this leadership into the 'beyond CMOS' world?

Yes, I think that Japan has always been superior in the development of new materials. As we know, Japanese companies including Toshiba, NEC and Hitachi, took the lead in the field of semiconductors up to the 1980s in parallel to Intel. Now the former's share in semiconductors is occupied by many foreign companies such as Samsung Electronics. However, now is good timing for Japan to get back to the top of the field with "Beyond CMOS".

You have had to collaborate with researchers from other disciplines to further your studies. How did you find this and did it give you new insight into your research?

I have worked in the international center for young scientist at the National Institute for Materials Science, where many promising candidates with different research fields are gathering from all over the world. Collaborations with researchers with different research backgrounds give us new ideas and concepts and help us push ahead with the realization of our proposed devices.

Beyond Moore's Law

As the inexorable capacity gains in traditional silicon electronics begin to falter, scientists are starting to search for new solutions to our computing needs. Dr. Ryoma Hayakawa is focusing on providing a bridge from the old world to the new.

CAPACITY CRUNCH

In 1965 Gordon Moore, co-founder of Intel, observed that the number of transistors per square inch on integrated circuits had doubled every year since the technology had been invented and he predicted this trend would continue for the foreseeable future.

He revised his prediction to a doubling every two years in 1975, but for decades his prediction has held firm. Now though, the continuing miniaturisation of traditional silicon electronics has begun to reach its limits as both power consumption and cost of production start to push back.

This has prompted researchers to start the search for the successor to the complementary metal-oxide semiconductor (CMOS) technology that powered last century's computing revolution. Among them is Dr. Ryoma Hayakawa from the International Center for Materials Nanoarchitectonics, Tsukuba, Japan.

MOLECULAR ELECTRONICS

One promising avenue for taking electronics 'beyond CMOS' is single molecule devices, which utilises single molecules as electronic components in transistors and memories. They make it possible to control circuits at the level of individual electrons.

Such devices not only hold the possibility of dramatically reducing both the size and speed of circuits, but they also demonstrate various quantum effects that could herald entirely new approaches to computing.

The development of such devices, however, is still very much at the level of basic science. A major obstacle to their widespread adoption is their lack of compatibility with standard CMOS technology. Solving this problem is the focus of Hayakawa's work.

"Our approach meets the requirements of both fields – the incorporation of new functions into current transistors and large-scale integration of realistic molecular devices," he says.

ORGANIC ELECTRONICS

Having worked in both the silicon and molecular electronics fields, he appreciates the benefits that both can provide. And so rather than attempting to build an entirely new architecture from the ground up Hayakawa has instead focused on integrating attractive molecular functions into silicon-based devices.

Alongside his collaborators he has integrated functional organic molecules into a metal-oxide semiconductor (MOS) structure, a basic component in current silicon transistors and memories.

The organic molecules are in the form of quantum dots – tiny particles that exhibit quantum physical effects. Traditionally these dots are made from inorganic molecules, but using organic molecules instead has several major advantages.

The molecules have a uniform size at the nanometre scale unlike their inorganic counterparts, which is important as non-uniform size hinders the ability of devices to operate in a stable way at room temperature. Uniform size also makes it possible to have a much higher density of dots, which boosts device capacities.

In addition, their energy levels are easily tuneable via the attachment of functional groups, such as electron-withdrawing or donating groups. Using photochromic or magnetic molecules also introduces the possibility of controlling the electrical properties of devices using light or magnetic fields.

"These unique features in organic molecules make them superior to inorganic dots" says Hayakawa. "Our proposed device, therefore has the potential to break through the limit of conventional silicon-technology and to integrate novel functionalities into conventional CMOS devices."

QUANTUM CONTROL

So far the results have been promising. Hayakawa's group has successfully demonstrated resonant tunnelling, which is a quantum transport, through molecular dots in a silicon-based double tunnel junction, where organic molecules are embedded in insulating layers in a MOS structure.

The group has demonstrated the effect in various molecules, but the most promising was their experiments with C60 molecules where resonant tunnelling was visualised even at 280 kelvin, which is almost room temperature.

In most cases transports are still limited to cryogenic temperature, but Hayakawa says the result prove the usefulness of organic quantum dots for controlling tunnelling current among other things.

“The proposed device can manipulate quantum transports such as resonant tunnelling and single-electron tunnelling,” says Hayakawa. “These features could lead to the realisation of extremely low power consumptions and high-speed operations.”

In addition the group has achieved two novel and attractive molecular functions unique to organic molecules in their silicon-based double tunnel junction - multilevel operation of resonant tunnelling and optical switching with photochromic molecules.

BOOSTING THE BITS

Current transistors and memories operate on a binary basis meaning only one bit of information can be manipulated at a time. Enabling multi-valued operation capable of manipulating multiple bits at a time could drastically reduce the number of components and interconnections on a chip enabling higher switching speeds and lower power consumption.

One way of achieving multi-valued operation is by controlling the energy levels of the molecules forming quantum dots. Organic molecules are particularly useful for this as the energy levels of these molecules can be varied markedly just by fluoridation, without changing the basic molecular frame.

Hayakawa’s group has fabricated a binary-molecule-based double tunnelling junction, in which both F16CuPc and CuPc molecules are incorporated together in an insulating layer. They observed multiple staircases reflecting the energy levels of the respective molecules, which indicates the potential for multilevel operation of resonant tunnelling with multiple molecules - something not possible with inorganic quantum dots.

“In inorganic quantum dots the interval in threshold voltages is decided by charging energy, which depends on the size of the quantum dots,” says Hayakawa. “In inorganic quantum dots, the change in dot size is a serious problem directly connected to the instability of devices at room temperature.”

LIGHTS CAMERA ACTION

The group has also experimented with optical control of resonant tunnelling using a derivative of diarylethene molecules to form optically controllable quantum dots. Importantly the optical control causes minimal change in the molecular geometrical structure so it should work even in a solid-state matrix. Their findings suggest the approach could allow the integration of photonic functionality into current silicon-based memory devices. Hayakawa says, “The construction of optical interconnection networks is a major topic because the complexity of interconnections in integrated circuits is a bottleneck for improving transistor performances. The delay in response with the increase of interconnections and the degradation of devices due to overheating are serious problems in current CMOS devices.”

Now Hayakawa is working on integrating these novel molecular functions into a vertical tunnel transistor with a double tunnel junction to realise a realistic molecular device. In recent preliminary work his group managed to fulfil basic transistor operations with their prototype.

“The most important thing is that our study demonstrates another direction in the strategy to develop future CMOS architectures,” says Hayakawa. “Our attempt has enormous potential for providing a breakthrough in silicon technology. But there are many obstacles to overcome in the realisation.”

RELATED MANUSCRIPTS

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Dr. Ryoma Hayakawa is an independent scientist at the International Center for Materials Nanoarchitectonics MANA at the National Institute for Materials Science in Japan. He received his undergraduate, masters and PhD in Engineering from Osaka Prefecture University, completing his studies in 2006. His research activities are focussed on integrating molecular electronics and standard silicon electronics. He also investigates the potential of organic field-effect transistor. Alongside fellow researchers he holds patents on a method for forming oxynitride and nitride films, a type of field-effect transistor and a dual-gate organic thin film transistor.

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