Devices, Materials, and Packaging Technologies for Hyperconnected Cloud

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The progress of Hyperconnected Cloud (HyCC) sustaining the coming Internet of Things (IoT) era means that novel hardware technologies are needed for collecting data from the real world and for high-speed data processing with limited space and energy consumption. To collect novel data and enhance HyCC coverage, several kinds of compound semiconductor devices have been developed for wireless telecommunication equipment, millimeter-wave radars, and odor sensors. Advanced packaging technologies such as 3D device integration for minimal chip-to-chip distance and compact optical transceivers with maximum bandwidth are developed, for compact, high-speed, and cost-effective products. New materials breaking through the limitations of information and communications technology (ICT) are under development including nanocarbon, by combining a novel build-up synthesizing process with a materials informatics approach. This paper presents the devices, materials, and packaging technologies developed in Fujitsu Laboratories.

1. Introduction

In the Internet of Things (IoT) era, all kinds of data will be connected, digitized, and processed in a huge virtual space to generate new values. Fujitsu Laboratories has set a new information and communications technology (ICT) platform of Hyperconnected Cloud (HyCC) to lead and accelerate the trends.1)

Figure 1 shows the concept of HyCC.2) Things, people, information, and services in the real world are plotted on the surface of a hemisphere of a virtual world. ICT infrastructures are placed in the center of the virtual world and cross-connect all the data from real things through digital equipment such as public clouds, private clouds, mobile, and IoT.

The sustainable development of HyCC needs not only software advancement but also a hardware breakthrough, in which the device technologies are the key especially for high-fidelity data collection from the real world and for making all the systems compact, energy efficient, and high speed.

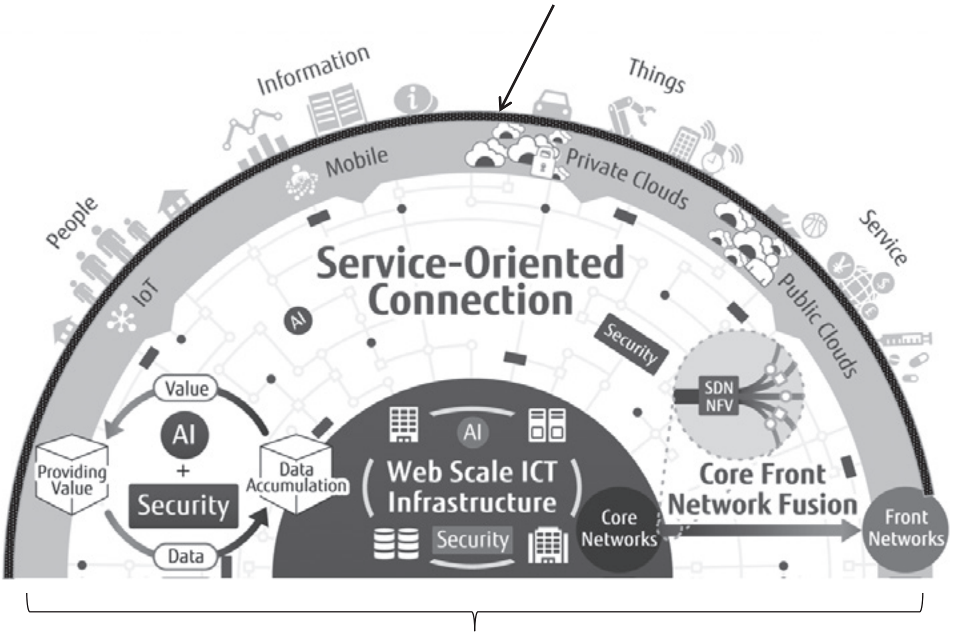
As a way to collect data from the real world, big data analysis is attracting a great deal of attention, trying to find hidden laws from general data-gathering from massively widespread sensors.

Pioneering the new frontier, however, is also important for enhancing the HyCC, and moving into areas such as cosmic space, the deep sea, and inside of the body. Development of special sensors with high sensitivity will be the key for that.

A huge increase in the amount of data is expected in line with IoT development; however, we have limited hardware resources in terms of footprints and power consumption for processing at a macro level. And they have to be kept at roughly the current level. HyCC consists of a wide variety of equipment from datacenter servers to edge servers, and automotive computers, but the above challenges are almost the same for all of them. Development of elemental technologies is of primary importance.

This paper presents the R&D activities related to compound semiconductor devices in Fujitsu Laboratories for high-sensitivity sensors. Then, it describes Fujitsu's high-density packaging technologies for compact, high-speed and power-effective ICT. Finally, it introduces one example of our leading-edge basic research, nanocarbon material, combining novel process technologies with a materials informatics approach.

Device technologies for advanced sensing and actuation



High-density packaging for compact, high-speed and cost-effective systems
New materials overcoming the limitations of ICT

Figure 1
HyCC and its core technologies.

2. Device technologies for advanced sensing

Almost 90% of today's semiconductor devices in the world are based on a single chemical element, silicon. The others are based on two or more elements and are generally called compound semiconductor devices. Compound semiconductors are well used in analogue applications where material properties define the device properties such as high frequency and high voltage resistance, while devices for digital signal processing are dominated by silicon because of its high integration capability. Compound semiconductor devices are especially important for extra-sensitive sensors that handle imperceptible analogue signals in the real world.

Fujitsu Laboratories has been leading this technical field since the invention of a high electron mobility transistor (HEMT) by Dr. Takashi Mimura in 1979. HEMT is a field-effect transistor incorporating a junction between two compound semiconductors with a layer of highly mobile conducting electrons there, and that allows HEMT to operate at higher frequencies than ordinary transistors. We have developed several kinds of material combinations based on the HEMT structure for different applications as shown in **Figure 2**.

Commercialization of HEMT devices started by combining GaAs and AlGaAs in a microwave telecommunication amplifier, which is widely applied in parabolic antennas for satellite broadcasting, and popularized the service with miniaturized antennas. Automotive radars at the early stage also used a HEMT of GaAs/AlGaAs and utilized the millimeter-wave sensing market.

HEMTs with an InP substrate were developed next. They are devices operating at the highest frequency ever, up to the terahertz region. InP HEMTs are expected to be applied to a variety of novel sensing uses including wideband wireless telecommunications, space probes, non-destructive material inspections, food componential analysis, and so on.3)

HEMTs with a GaN substrate are suitable for high-power applications because of their high voltage resistance, and they have already been commercialized for use in wireless base stations. GaN HEMTs are expected to be applied to long-distance radars, power supply units, and microwave heating.

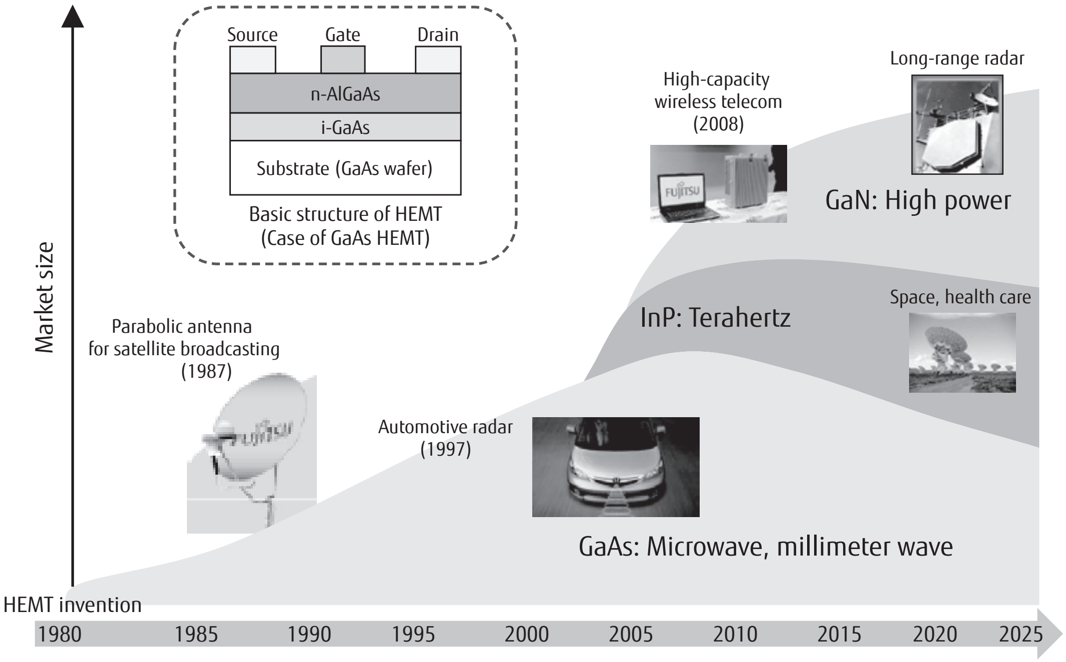


Figure 2
History of HEMT material.

Fujitsu Laboratories also develops other kinds of sensing devices such as odor sensors, which are the most poorly developed of all sensors that relate to the five senses of humans.

Today's odor sensors do not perform well enough to be substituted for or supersede the human nose, although a wide variety of applications are expected such as checking the freshness of food and its origins, performing initial diagnostic tests, and so on. Fujitsu Laboratories is trying to build-up odor sensing systems using newly developed high-sensitive odor sensors based upon the experience and know-how it obtained from developing compound semiconductors.

3. Packaging technologies for compact, high-speed, and power-effective ICT

The data traffic in an ICT network will increase at an annual rate of 23% in the coming IoT era.4) As mentioned above, this traffic increase has to be handled with no additional size and power supply provided to the current ICT infrastructure, for sustainable growth.

In a few decades, semiconductor devices and related hardware have led ICT progress with downsizing, cost-cutting, and upgrading. The scaling of silicon MOS devices and the following packaging development has miniaturized supercomputers in the twentieth century into today's smartphones.

Silicon scaling has been slowing down since 2010, because of physical limitations in processing technology and difficulties related to the huge finance capital expenditure that is required. This financial aspect reduced the number of silicon MOS venders, so that only a few companies now survive in the areas of processors, DRAMs, and so on.

In the current situation where there is uniformity between core devices, original packaging technologies come to be essential to realize higher performance ICT products than competitors in the following three technical fields:

1) High-density packaging

Having short wiring between devices is a very effective way to reduce signal propagation delay, loss, and overall packaging size. The technology tends to need fine and expensive wiring lines on a substrate close to those with a semiconductor process, and has been applied only for high-end products such as supercomputers.

In the coming HyCC platforms, there will be increasing demand for compact and high-power servers for uses such as automated car driving,5) which need a performance that is comparable to one high-end server rack but with one-tenth to one-hundredth of the volume.

Figure 3 shows a device packaging roadmap mainly for server applications. Interposers made of a silicon substrate with a semiconductor-class process will realize higher density wiring and overall product downsizing by a factor of 10, which is the so-called two-and-a-half-dimensional integrated circuit (2.5D IC). Using a three-dimensional integrated circuit (3D IC), stacking silicon wafers and/or dies and interconnecting them vertically through-silicon vias can give an ideally high density structure but it involves a very expensive process currently. The 3D ICs with multiple-chip stacking will realize much higher density by a factor of 100, and development of a cost-effective process will make them essential for future edge servers and car-mounted computers.

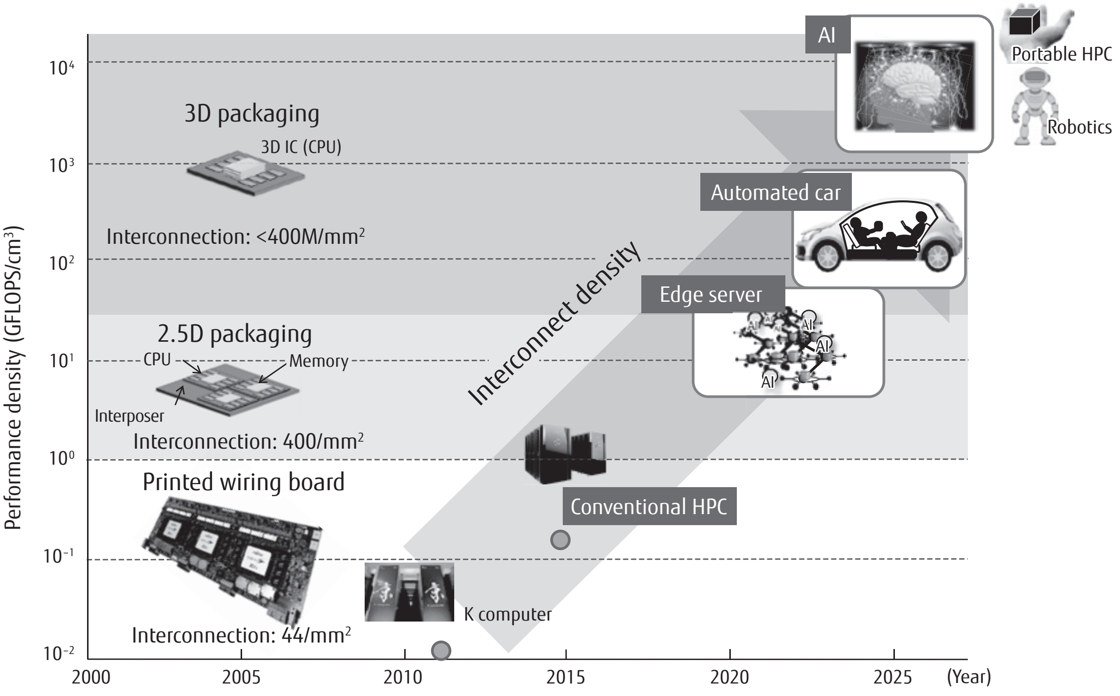
Future neuro-computers and brain-type computers need a great number of interconnects between processors, and the number is an order of magnitude larger than today's one.[6] At that time, a novel higher-density packaging technology will appear based on the current 3D ICs.

2) High-density optical packaging

For high-speed interconnection between ICT products, optical fibers with transceiver modules are being increasingly used, replacing the current tight and lossy co-axial cables for downsizing and energy efficiency. The future 2.5D/3D ICs mentioned above need smaller optical transceivers in their I/Os comparable with ICs. Silicon photonics is promising technology for high-density optics integrating the main transceiver functions on a silicon substrate including narrow-space optical wiring, in which silicon optical waveguides strongly confine light and turn it with much smaller diameter than the conventional glass waveguides. Fujitsu Laboratories is developing silicon photonics as next-generation high-speed interconnection technology after the current transceiver module, based on many years of combined know-how relating to compound semiconductors, silicon, and high-density packaging.

3) Cooling technology

Fujitsu Laboratories has developed highly reliable



AI: Artificial intelligence
HPC: High performance computing

Figure 3
Roadmap of device packaging technology for servers.

water cooling technology including coolant and related materials covering a whole system on a datacenter scale such as the K computer. The high-density packaging mentioned above, 3D ICs and silicon photonics, need finer scale cooling technology, focusing on hot spots inside ICs and their thermal paths to whole water cooling systems.

Circulating a coolant in such a small space is a big challenge because of channel microfabrication, flow rate and the pumping power needed for a large differential pressure. We developed a two-phase cooling system with coolant vaporization, which needs a much smaller flow rate than liquid cooling and allows self-circulation of coolant, similar to heat pipes, with a well-defined structure. We aim to have it applied to computers and also mobile products.

4. Leading-edge basic research of new materials

Novel devices often overcome the boundaries of traditional ICT and cause drastic social changes; however, they need a long time to develop in general. For example, in Fujitsu, HEMTs, surface acoustic wave (SAW) filters, and quantum dot lasers required many years of development. Fujitsu Laboratories selects several research items as leading-edge basic research which can be core technology in the next generation.

Nanocarbon, with help from materials informatics, is one such kind of basic research theme. The current major semiconductor material of silicon is approaching its physical limitations. Carbon belongs to the fourth element group with silicon; however, its potential for use as an electronics material exceeds silicon in terms of its conductivity and electron-mobility. Carbon-based semiconductors will possibly change the IoT world by realizing super-high-speed and energy-efficient transistors, or highly sensitive gas sensors.[7]

Fujitsu Laboratories has made world-class achievements in carbon nanotubes and graphene to date. We are currently focusing on graphene nanoribbons (GNR), which are strips of graphene with an ultra-thin width (<50 nm), and their properties drastically change depending on the direction and width. We are trying to find a methodology to control GNR properties with a combination of structural design, achieved with supercomputer simulation, and novel processing technology, achieved with bottom-up chemical synthesis (**Figure 4**).

5. Conclusion

The current situation and future direction of R&D in devices, packaging technologies and advanced materials in Fujitsu Laboratories has been introduced here.

HyCC platforms are moving forward with development of both software and hardware. Virtualization technology, called software-defined anything (SDx), is well developed these days, where the conventional hardware-specific functions are replaced with software. That is an effective way to decrease special-purpose hardware products. However, it needs more powerful hardware than ever. That means we have to produce breakthrough technology also for hardware to support the coming rapid development in software. Most of the R&D items introduced in this paper will be realized in future ICT products, and will take HyCC platforms to the next stage.

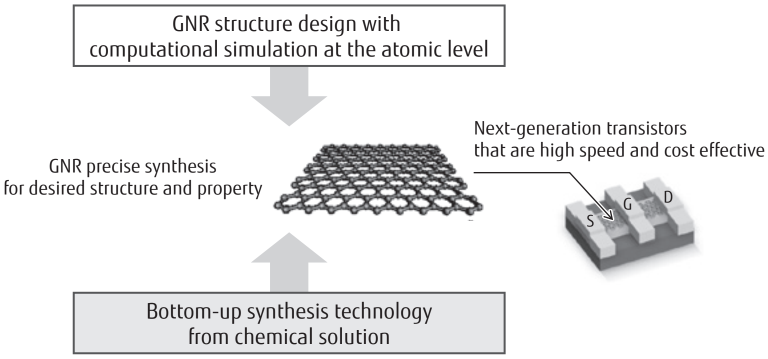


Figure 4
Tailored synthesis of graphene nanoribbons (GNR).

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