NEC Group & Nanotechnology – Opening a Path to the Future

Paving the way for an Information Society of unprecedented convenience and comfort, NEC has been tackling the development of nanotechnology since the late eighties as the key to innovative technologies that will unlock advanced information technologies and network system infrastructure. This special issue will introduce NEC's proprietary fundamental technologies and examples of our groundbreaking nanodevice technologies as well as our development strategy which is applying the unique physical phenomena of nanostructures to innovative nanodevices, our leveraging of open innovation through collaboration with third parties, and our global edge in nanomaterials, nanofabrication and nano-evaluation and new nano-simulation technologies.

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1 Introduction

As a result of the rapid and widespread adoption of cellular phones, personal computers and Internet usage in recent years, we not only enjoy simpler communications on a global scale but also have the capability to easily gather information from the four corners of the world. And the future holds expectations for even more convenience enabled by faster networks and a more robust mobile environment as well as demands for higher information security. In order to realize this vision, it will be necessary to develop network, IT and mobile devices that have higher performance, more compact design, lower energy consumption and lower prices than ever before. On the other hand, obstacles such as semiconductor fabrication scaling limits, which are critical to enhancing electronic device performance, and insufficient battery capacity, which is handicapping the expanding functionality of mobile devices, are becoming more apparent. This situation has necessitated development of paradigm-shifting technologies, materials, devices and equipment. The creation of innovation on this level will require the technological development based on new physics and science. Among them, nanotechnology (nanotech) – the practical application of the unique properties and phenomena of the nano-world – is considered to have the biggest potential of making this possible. As shown in **Fig. 1**, nanotech is expected to find application beyond the domain of IT networks and revolutionize a variety of fields including medical care, the environment, and energy. Since the USA introduced the world to the term nanotechnology with its launch of the National Nanotechnology Initiative (NNI) in 2000, the term has come to describe an extremely broad range

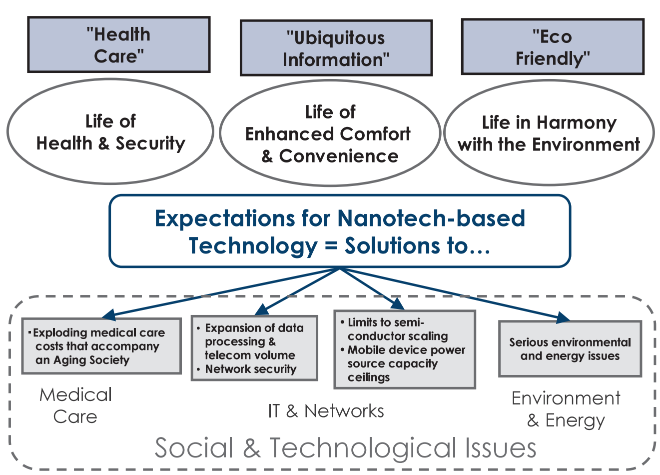

Fig. 1 Expectations for nanotech in the future.

of concepts; however, this article will limit its scope to the technologies that exploit the unique phenomena that occur in the nanometric domain.

In these pages, our focus will be on the technologies that lead to the next generation of services, and specifically those services that will take advantage of the huge leap in performance and power consumption efficiency expected from the network equipment and IT/mobile devices of the future. We will begin with a description of NEC's nanotech development strategy and fundamental nanotechnologies, and then introduce some of the device technology resulting from our research and development to date.

2 Nanotech Development Strategy

As shown in **Fig. 2**, NEC aims to play an important role in building the safe, secure and comfortable Ubiquitous Information Society of tomorrow. With this goal in mind, we are already making major advances in developing not only the next-generation network (NGN) which will seamlessly interweave ultra-high-speed networks with unprecedented security and deliver a convenient and comfortable access environment, but also the various technologies that will provide the next generation of services that will be carried by NGN. Among the many avenues of research being pursued by NEC, nanotech carries the highest expectations as revolutionary technology capable of realizing the remarkable leaps in speed, power efficiency and miniaturization demanded by future IT network infrastructure and mobile equipment. In this section, we will provide a brief outline of NEC's strategy for nanotech development.

Fig. 3 shows a conceptual map of NEC's nanotech development strategy. With the aim of creating an IT society that is eco-friendly and enjoys the advantages of information ubiquity and enhanced health care, we have formulated a strategy of 1) solidifying a foundation of NEC's globally leading nanotech fundamental technologies; 2) conceiving original ideas with practical device applications inspired by physical phenomena and properties unique to nano-structures; and 3) developing ground-breaking devices and products that far surpass current performance levels.

NEC began development of fundamental nanotechnologies in the late1980s. Today our technology ranks among the most advanced in the world and spans areas from nanoscale material fabrication such as carbon nanotubes (CNT) and 10nm-scale patterning technology using electron beam exposure with high-resolution resist to various nano-level evaluation technologies such as high-resolution transmission electron microscope (TEM) technology, scanning tunnelling microscopy (STM) and even computer simulation technology that applies scientific computations to clarify nanoscale physical phenomena and chemical changes at the atomic or molecular level. These advances are providing a deeper understanding of nanometric phenomena and freeing us to create nanometric-scale materials and structures.

Nano scale does not simply mean that things are smaller or lighter. In the nano world, materials behave quite differently than in the macro world with which we are most familiar. They exhibit different physical and chemical properties that result in unexpected phenomena that are not only unique to materials on the nano scale but also hold the potential to unlock barriers that conventional technology has been unable to break through. The

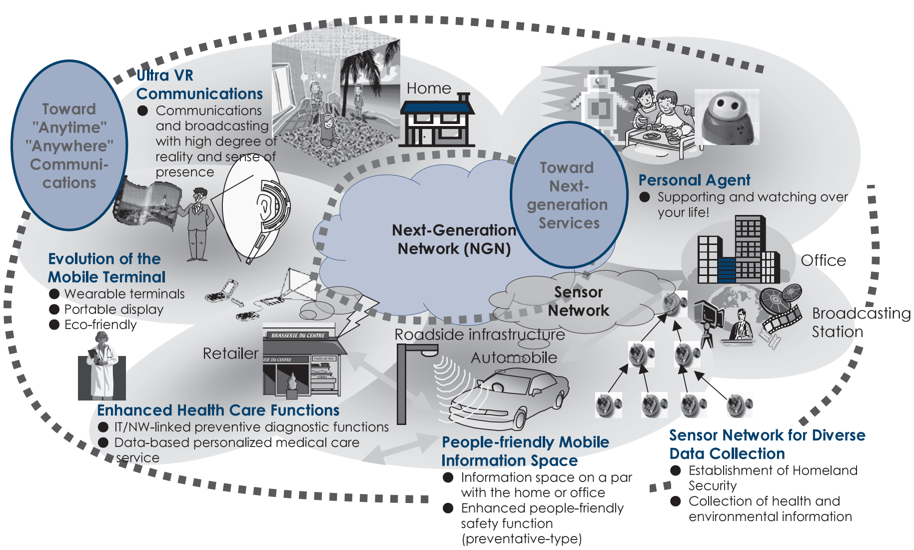

Fig. 2 Impact of NGN on future lifestyles.

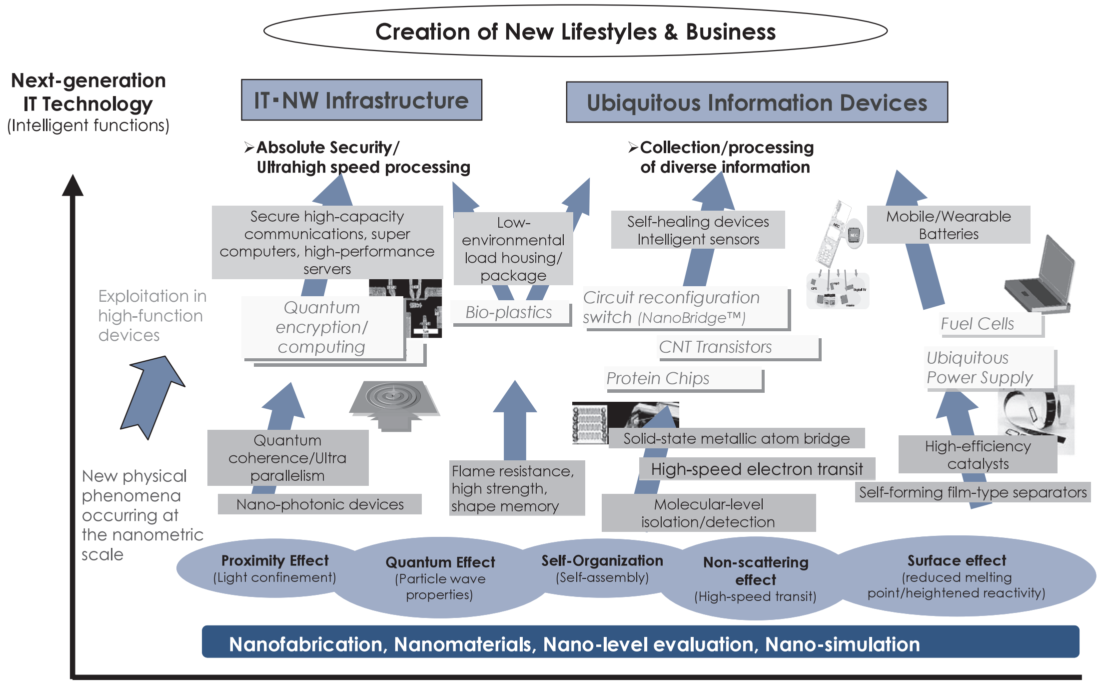

Fig. 3 NEC's nanotech development strategy.

typical phenomena observed at the nanoscale include: the proximity field effect and its confinement of light; the quantum effect that magnifies particle wave behavior and other properties; self organization that may hold the key to self-assembly; the non-scattering effect that ensures collision-free high-speed electron transit; and the surface effect which results in a significantly reduced melting point or increased reactivity. By applying our proprietary fundamental technologies such as nano-evaluation and nano-simulation to better observe, experiment and compute the nature of these phenomena, we gain a profound understanding that sparks the creation of ideas which in turn leads to paradigm-shifting materials and devices.

In order to transform ideas into reality, we prototype actual devices using nanomaterials and nanofabrication technologies, and then verify their behavior. For example, we successfully combined our nanofabrication technology and carbon nanotube (CNT) growth technology to prototype a high-performance CNT transistor – a feat that would be impossible using conventional semiconductor fabrication processes. The prototype achieved operational performance more than 10 times that of Si transistors currently used in LSI circuits.

On the other hand, the development of innovative nanotech-based materials and devices is a task beyond NEC to undertake alone. While it is very important to find and cultivate new seeds of technology in the broad nanotech landscape, this would be very difficult to accomplish with only our vast but limited resources. For this reason, we are aggressively pursuing a strategy of "open innovation" which encourages collaboration among the private, public and academic sectors as shown in **Fig. 4**. We are actively seeking collaboration with the many universities and public research institutions (independent administrative institutions) that are engaged in "seed technology" research in the broad and varied domain of nanotech. When we identify research themes that are attractive from the perspective of our own R&D efforts with an enterprise's eye on its commercialization potential, we then fast-track highly solution-oriented research and development that puts a priority on the practical ap-

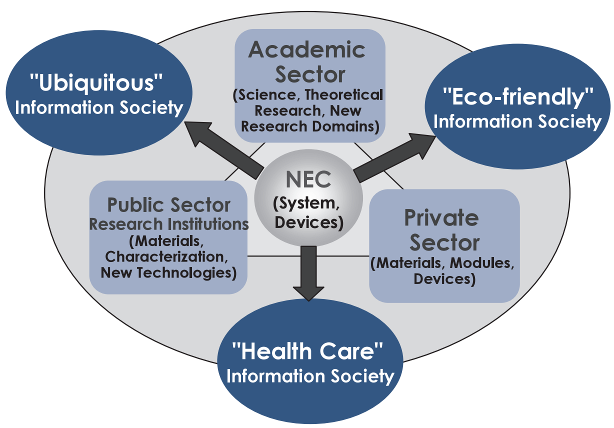

Fig. 4 "Open Innovation" Model.

plication of the technology.

The NanoBridge™ is a good example of our open innovation approach to development. Research and development of this unique device that will enable circuit reconfiguration even after the fabrication of the LSI is being undertaken in collaboration with the National Institute for Materials Science (NIMS). We also conduct joint research with the Advanced Industrial Science and Technology (AIST) into the high-quality ceramic thin film fabrication by means of aerosol deposition (AD). This technology is expected to lead to development of high-performance optical devices and magnetic field detection devices.

3 The Fundamentals of Nanotech

Next let's take a look at some of NEC's fundamental nanotechnologies. Shown in **Fig. 5**, our nanomaterial, nanofabrication, nano-evaluation, nano-simulation and other fundamental technologies possessed by NEC rank among the most advanced in the world. Beginning with the discovery of CNT by Dr. Iijima in 1991 and subsequent development of carbon nanohorn (CNH) growth technologies, NEC has continued to explore practical applications of these key materials while expanding the frontiers of nanomaterials with the exploration of new categories. One example is ceramic thin film fabrication technology based on aerosol deposition (AD) - an innovative process that directly deposits complex oxide films consisting of nanoparticles.

In the field of electron beam lithography technology which has almost 20 years of development as a nanofabrication technology behind it, NEC and Tokuyama Corporation have collaborated on the development of technology that uses calixarene resist, which enables patterning on the scale of 8nm. Such technologies are opening the way for 10nm-level processing.

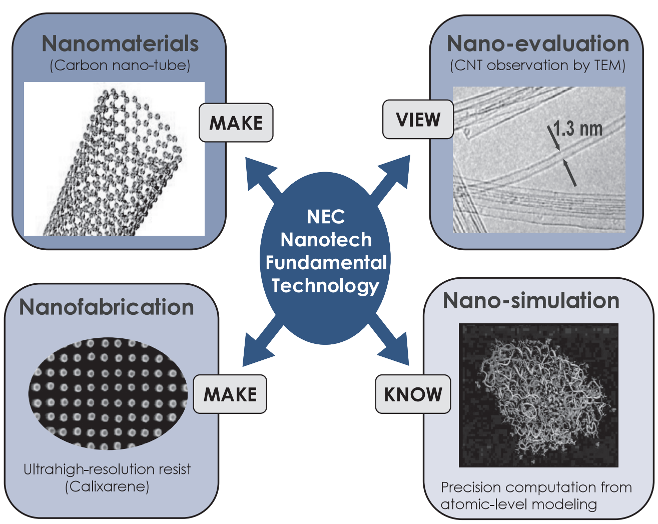

Fig. 5 NEC's fundamental nanotechnologies.

As a pioneer in the field nano-evaluation technologies, we possess the world's most advanced transmission electron microscopy (TEM) technology, capable of imaging structure and motion at the atomic level. It is this technology that enabled the discovery of carbon nanotubes (CNT), incredible structures are essentially single atom-thick graphite sheets rolled into tube-like structures with a diameter of only a few nanometers. With the capability to capture not only static images but also observe the dynamic CNT growth process from its catalyst, this technology is expected to play an important part in clarifying the growth mechanism of CNT.

Our nano-simulation technologies span first-principles computation technology for calculation of the state after aggregation of atoms or molecules based on their original energy states prior to aggregation, and simulation technology for calculating the interatomic electroconductivity. Since 1990, NEC has developed a number of proprietary nano-simulation technologies related to nano-scale investigation of Si, CNT and other materials. While such calculations demand vast computational resources, NEC is able to perform the necessary large-scale, high-speed calculations using vector-type supercomputers that have been developed and commercialized by our company.

These world-class fundamental nanotechnologies possessed by NEC are enabling us to take the lead in the research and development of new nanodevices.

4 Nanodevice Technology

Fig. 6 shows just a few examples of nanodevices developed at NEC. In this section, we will briefly describe their characteristics and applications.

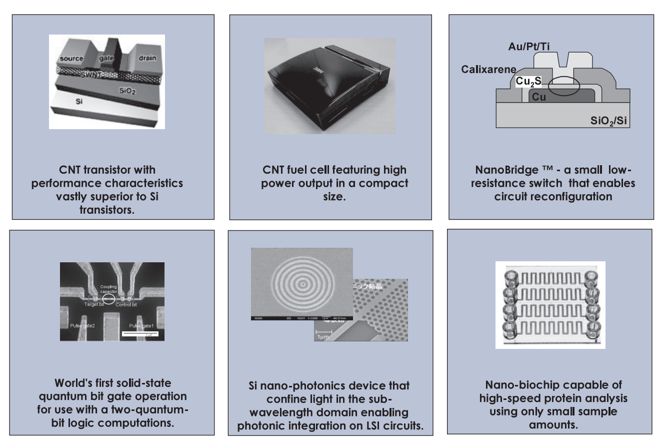

Fig. 6 Examples of nanodevices developed by NEC

It is theorized that the transit of electrons CNT will be free from the scattering effect, and hoped that this phenomena can be applied to the development of high-speed transistors. NEC has already prototyped a CNT transistor and demonstrated transconductance (index of speed) 10 times larger than that of Si-MOSFET used in current LSI. Because this device can be fabricated on any type of substrate, it is considered as a way to achieve high-speed electronic circuitry at low cost without microfabrication processes. Not only LSI fabrication but also displays and integrated sensors are expected to benefit from the application of this technology and the advantage of low-cost fabrication of electronic circuits on a large area.

Carbon nanohorns (CNH) are a kind of CNT that are aggregates of conic structures. The unique shape and properties of CNH provide an optimum support material for the uniform, high-density distribution of nanometric-sized platinum catalyst particles, resulting in the optimum electrode material for mobile fuel cells. Using this electrode material, NEC has already prototyped a fuel cell, verified the high performance of 100mW/cm^2 and demonstrated its possible application as a power source for notebook PCs.

By stretching and shrinking the length of nanometric-size thin Cu bridge needles inside a solid-state electrolyte (Cu_2S) film, the NanoBridge™ switching device causes a significant variance in the electrical resistance between wiring, effectively resulting in a switch. Moreover, it can preserve the changed status even after the power supply is shut down. The basic operation of the device has been verified, and a test circuit has been fabricated on LSI and the basic operations required for non-volatile memory and a circuit switch have been confirmed. One of the most exciting potential applications of this technology is its integration as non-volatile switch that enables circuit reconfiguration.

Complex calculations that would take years for a conventional computer to complete will be crunched in an instant by the quantum computers of the future, and the “qubit” or solid-state quantum bit is the basic element for quantum computation. Using a superconducting tunnel junction, NEC has configured a quantum gate and verified solid-state 2-quantum bit operation for the first time in the world. With the aim of transforming this landmark development into practical technology, we are endeavouring to increase the number of bits and develop quantum computation algorithms.

Si nano-photonic devices confine light in the sub-wavelength domain, enabling the reduction of both the size and power consumption. NEC has already verified that thin Si wire can be used as light guides or add/drop multiplexers, and that an infinitesimally small Si nano-photodiode equipped with a plasmon antenna originally fabricated by NEC can operate at 50GHz or higher. This development not only may lead to smaller optical communication devices that boast high performance and low power consumption and can be produced at low costs, but

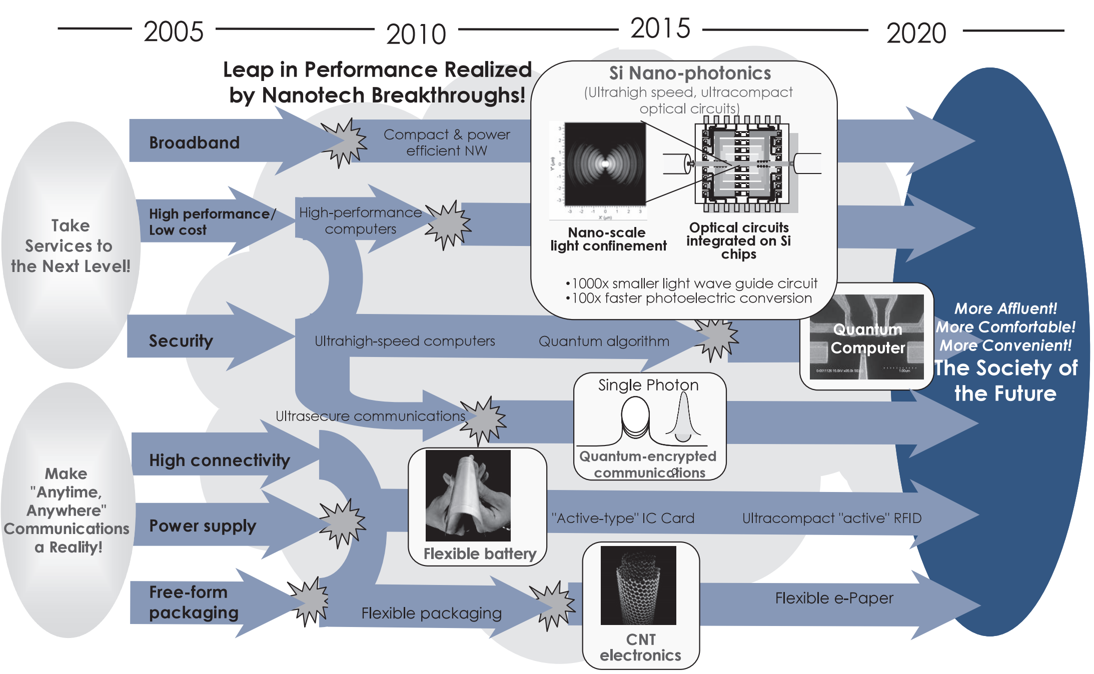

Fig. 7 NEC’s development vision for nanotech materials and devices.

also may have broader application as optical interconnections between boards or LSI chips or in optical wiring inside LSI.

Nano-biochip development is progressing toward its goal of improving protein assay. A multiple arrangement of thin pillars of biochips creates a long channel, facilitating high-throughput and efficient protein separation according to their chemical properties followed by measurements using a mass spectrometer. NEC has already verified fundamental operation, and is planning to take development to the next stage in the clinical arena where issues will be identified and solved.

5 Conclusion

In the above article, we have attempted to paint a broad picture of our nanotech development strategy and proprietary fundamental nanotechnologies together with an outline of nanodevice technologies that have already been produced by our ongoing research and development. The heart of our nanotech development strategy lies in encouraging open innovation practices that leverage 1) NEC's world-class foundation of fundamental nanotech technologies; 2) the conception of original ideas that lead to practical exploitation of physical phenomena unique to nano-structures; and 3) the development of devices and products that deliver unprecedented performance. Attracting worldwide attention, NEC's proprietary fundamental technologies in the fields of nanomaterial, nanofabrication, nano-evaluation and nano-simulation will be used to gain a deeper understanding of the phenomena unique to the nano domain and to inspire innovative ideas that exploit these insights and lead to development of nanodevices with innovative functions.

Fig. 7 graphically illustrates our chronological vision for our future development of several key nanomaterials and nanodevices – some of which have been introduced in detail in this special issue. With the aim of providing revolutionary technology that will make possible NGN infrastructure and IT/mobile equipment, NEC will encourage more external collaboration using our open approach and will press forward with research and development to bring nanotech and nanodevice technologies into practical use as early as possible.