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PRESS RELEASE
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World's first elastic conductors
~ Rubber-like stretchable integrated circuits that can cover curved surfaces ~

Tokyo, Japan, August 7, 2008:
A research team led by Dr Takao Someya from the University of Tokyo has successfully developed the world's first elastic conductors using single-walled carbon nanotubes (SWNTs) as a conducting dopant. The measured value of conductivity is the highest in the world (57 S/cm) for chemically stable elastic materials, and it is two orders of magnitude greater than the conductivity value of previously reported SWNT composite polymers. Such high conductivity is achieved because the content of SWNTs in the conductor can be increased up to 20 wt% without sacrificing mechanical flexibility and softness. The SWNT elastic conductor can be stretched to approximately 134% of its original size without significant mechanical damage. The team has also successfully fabricated rubber-like stretchable integrated circuits (ICs). The abovementioned elastic conductors are integrated with organic transistors, which are fabricated by state-of-the-art printing processes, and are then used as wirings in large-area stretchable ICs. These ICs, which have a high electronic performance, can be stretched by up to 70% without any degradation in their mechanical or electronic properties. This is an important step in the development of ICs that can be used on freely curved surfaces and in smart surfaces. Subsequently, it will be possible to develop an intelligent surface that will be able to interact with people, objects, and the environment in new ways. The project is carried out in collaborations with Dr. Tsuyoshi Sekitani, the University of Tokyo, Dr. Takuzo Aida, the University of Tokyo, Dr. Takanori Fukushima, Advanced Science Institute, RIKEN, and Dr. Kenji Hata, National Institute of Advanced Industrial Science and Technology. Details of the technology are to be published in Science, within the Science Express web site, on 07 August 2008.

Dr. Someya and his coworkers have successfully developed the world's first elastic conductors using single-walled carbon nanotubes (SWNTs) as a conducting dopant. The measured value of conductivity is the highest in the world (57 S/cm) for chemically stable elastic materials. Such high conductivity is achieved because the content of SWNTs in the conductors can be increased up to 20 wt% without sacrificing mechanical flexibility and softness. The key to the fabrication of highly elastic conductors and gels with high conductivity lies in the utilization of fine bundles of millimeter-long SWNTs that are produced by grinding the SWNTs with ionic liquids, followed by uniform dispersion in compatible fluorinated copolymer matrices. The elastic conductors are integrated with organic transistors, which are fabricated by state-of-the-art printing processes, and are then used as wirings in rubber-like stretchable large-area integrated circuits (ICs). These ICs that have a high electronic performance can be stretched up to 70% of their original size without any degradation in their mechanical or electronic properties.

///// **Fabrication** /////

Elastic conductors are fabricated by dispersing SWNTs as a chemically stable conducting dopant in fluorinated copolymer matrices. It is well known that multiple SWNTs tend to aggregate together due to the strong intermolecular force between them; this results in the formation of bundles of SWNTs, which makes it extremely difficult to uniformly disperse the SWNTs in a polymer matrix. In order to overcome this problem, fine bundles of millimeter-long SWNTs are produced by grinding the SWNTs with ionic liquids, giving rise to a black paste-like substance, referred to as "**bucky gel**." The bucky gel is steadily added to a fluorinated copolymer and the mixture is then poured onto a glass plate by drop casting to obtain SWNT composite films (**SWNT films**). Subsequently, the SWNT films are coated with silicone rubber to obtain "**elastic conductors**." In order to improve their elasticity, some samples are mechanically processed using a punching system and are transformed into perforated films with a net-shaped structure.

///// **Conductivity** /////

The fabricated elastic conductors exhibit an extraordinarily high conductivity value of 57 S/cm. This value is the highest value of conductivity in the world for chemically stable elastic materials, and it is two orders of magnitude greater than the conductivity value of previously reported SWNT composite polymers. The key to the realization of this novel fabrication process is the uniform dispersion of SWNTs into fluorinated copolymer matrices. The high conductivity of these conductors is achieved by solving the well-known problems associated with aggregation of the SWNTs. It should be noted that the content of SWNTs in an elastic conductor can be increased by up to 20 wt% without sacrificing mechanical flexibility and softness. However, the increase in the content of carbon nanotubes in polymer matrices makes it more difficult to realize uniform dispersion of the nanotubes due to aggregation, resulting in degradation in the conductivity and/or softness.

///// **Mechanical characteristics** /////

The new materials do not show any mechanical damage or significant changes in conductivity when they are uniaxially stretched by 38% or less. To our knowledge, there exist no other highly conductive materials that do not exhibit changes in conductivity under a large stretching stress exceeding 10%. Indeed, metal wires break when 1~2% strains are applied. The new materials posses this remarkable property because millimeter-long SWNTs, which are synthesized by the supergrowth method, are utilized as a conducting dopant in the fabrication. When the resulting net-shaped structures were tested, it was observed that they can be uniaxially stretched up to 134% of their original size; however, the conductivity decreased moderately with the application of tensile strain.

///// **Stretchable IC**/////

Taking full advantage of the properties of the SWNT elastic conductor and paste, a 19 × 37 organic-transistor-based stretchable active matrix was fabricated by combining printing, vacuum evaporation, and mechanical processes. The fabrication of rubber-like stretchable active matrixes is possible because of the numerous newly developed fabrication techniques and novel elastic conductors. For example, the team has fabricated via interconnections with extraordinarily high conductivity by combining mechanical processes and elastic gels. When the interconnections are stretched by 70% or less, the transistor characteristics without strain exhibit the same values as those measured before the stretching tests. Furthermore, no mechanical damages or changes in the electrical characteristics are observed even after 30 cycles at 70% stretching; this indicates the excellent electrical functionalities and stability of the active matrix under stretching.

///// **Backgrounds** /////

Organic semiconductor technology relies on carbon-based materials. The devices developed using this technology cannot achieve the high-speed performance of their silicon counterparts but their fabrication cost is much lower, and they are better-suited for fabrication on large-area, flexible plastic substrates. They can also be conveniently manufactured at ambient temperatures on plastic films using printing and/or roll-to-roll processes. The main motivation behind the recent efforts for the development of organic transistors has been the potential for their application in flexible displays and printable wireless tags. Someya and his coworkers have demonstrated another promising sphere of application—large-area, flexible sensors and actuators such as electronic artificial skin that can be used for future generations of robots (2003), sheet-type image scanners (2004), sheet-type Braille displays for blind people (2005), wireless power transmission sheets (2006), and communication sheets (2007). In particular, integrated circuits have been directly fabricated on plastic films and mechanically processed to form perforated films with net-shaped structures that serve as stretchable artificial skins (T. Someya, *et al.*, Proc. Natl. Acad. Sci. USA. 102, 12321, 2005). Net-shaped integrated circuits are flexible but have inelastic wirings. By using elastic wirings, their mechanical robustness can be improved significantly. Aida and Fukushima discovered a bucky gel by grinding bundles of SWNTs with ionic liquids in the framework of the JST/ERATO project (T. Fukushima, et al., Science 300, 2072, 2003). Subsequently, a new research project was launched in order to develop elastic conductors by utilizing bucky gels. Furthermore, millimeter-long supergrowth SWNTs (K. Hata, et al., Science 306, 1362, 2004) synthesized by Hata were exploited to realize elastic conductors with the remarkable property of not exhibiting changes in conductivity even under large strains.

///// **Stretchable electronics** /////

The realization of stretchable electronics is one of the most interesting challenges in material science and engineering. Stretchability is an entirely different concept from the miniaturization trend currently pursued by conventional electronics and has the potential to provide exciting opportunities, particularly in the sphere of large-area electronics. In the last decade, large-area electronic devices have become so thin and light that even large-area solar cells and displays can be easily hung on roofs and walls. It is expected that large-area electronic devices will now be developed further, making the realization of bendable and rollable displays possible. At the same time, large-area, flexible sensors and actuators are another emerging frontier. Although these achievements represent valuable advances, the utility of flexible electronics is limited to nearly flat substrates. In contrast, stretchable electronics can cover arbitrary curved surfaces and movable parts such as the joints of a robot’s arm, thereby significantly expanding the area of utilization of these electronics. Techniques to simultaneously improve the mechanical robustness and electronic performance are the keys to the realization of high performance rubber-like stretchable electronics. Rigid materials usually exhibit a good electronic performance and excellent controllability or stability, but their mechanical robustness is poor. On the other hand, soft materials show good mechanical properties but poor electronic properties. In this study, the team developed rubber-like transistor active matrices that can be stretched biaxially by up to 70% of their original size. The key was the fabrication of highly elastic conductors and gels with high conductivity. Elastomers or gels have not been previously utilized in the manufacture of integrated circuits; however, the present state-of-the-art techniques available in materials science and technology can improve the conductivities of soft materials to an extent where they can be used for wirings in integrated circuits.

///// **Future prospects**/////

The team has demonstrated the feasibilities of the SWNT-based elastic conductors and SWNT paste developed in this study by fabricating an active matrix. It should be noted that the materials and integration technology used in this study can also be applied to other types of electronic functionalities. This is an important step toward the development of infrastructure for the imminent era of ambient electronics, in which a multitude of electronic devices such as sensor networks will be used in our daily life to enhance security, safety, and convenience. By integrating a stretchable active matrix with a two-dimensional array of pressure sensors, rubber-like artificial skin can be obtained. Furthermore, if a stretchable active matrix is integrated with an array of actuators and mounted on to a curved surface, the touch feeling on the surface can be changed electrically. In this manner, the elastic conductors developed in this work enable the development of electronic circuits that can be mounted on surfaces where we have been unable to provide electrical functionalities to date. This is an important step toward the production of intelligent surfaces that can be used as friendly human-electronics interfaces. In the future, such intelligent surfaces will be able to interact with people, objects, and the environment in new ways.

///// **Publication** /////

Details of the technology will appear in the Science Express section of the Science magazine website on August 7, 2008, and it is also expected to be published in the September 5, 2008, issue of the Science magazine.

///// **Funding** /////

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Sample images

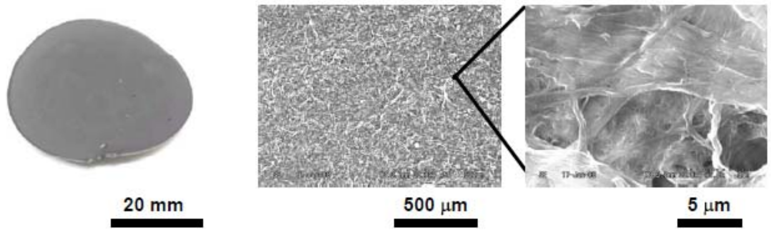

Figure 1: Actual image (left) and electron microscopic images (center and right) of an elastic conductor. The high conductivity of these conductors was achieved by employing a unique process that uniformly distributes carbon nanotubes in a two-dimensional cross-linked polymer matrix by unraveling the nanotubes using an ionic liquid.

Figure 2: Using the SWNT elastic conductors and paste, rubber-like stretchable ICs have been successfully fabricated, as shown above. Elastic conductors allow the development of electronic ICs that can be mounted on any surface, including arbitrary curved surfaces and movable parts such as the joints of a robot's arm. (Note: Transparent rubber (Sylgard184) is used as a substrate in order to show the inside of the structures.)

Figure 3: The fabricated ICs, which have a high electronic performance, can be stretched up to 70% of their original size without any degradation in their mechanical or electronic properties. Furthermore, no mechanical damages or changes in electrical characteristics are observed even after 30 cycles at 70% stretching. This indicates the excellent electrical functionalities and stability of the active matrix under stretching. (Note: White rubber (SH9555) with a stretchability of 440% is used as a substrate.)

Reference Material 1

Details of the technology are to be published in Science,
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Title: "A Rubber-like Stretchable Active Matrix Using Elastic Conductors"

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Abstract: By using an ionic liquid of 1-butyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide, single-walled carbon nanotubes (SWNTs) were uniformly dispersed as chemically stable dopants in a vinylidene fluoride-hexafluoropropylene copolymer matrix to form a composite film. We found that the SWNT content can be increased up to 20 wt% without reducing the mechanical flexibility or softness of the copolymer. The SWNT composite film was coated with dimethyl-siloxane-based rubber, which exhibited an extraordinarily high conductivity of 57 S/cm and high stretchability of 134%. Further, the elastic conductor was integrated with printed organic transistors to fabricate a rubber-like active matrix with an effective area of 20 × 20 cm^2. The active matrix sheet can be uniaxially and biaxially stretched by 70% without mechanical or electrical damage. The elastic conductor allows for the construction of electronic integrated circuits, which can be mounted on any place, including arbitrary curved surfaces and movable parts such as the joints of a robot’s arm.

Reference Material 2

FAQs

Q1: What is the main breakthrough achieved in this study?

A2: There have been previous reports on combinations of ***inelastic*** polymers and ionic liquids that are compatible with each other. However, in this study, the team has successfully discovered a combination of ***elastic*** polymers and ionic liquids that are compatible with each other. With this unique combination, SWNTs can be uniformly dispersed in elastic polymer matrices. This is one of the most important breakthroughs of this work.

Q2: Please specify the names of the materials needed to fabricate elastic conductors.

A2: In order to create a unique combination comprising elastic polymers and ionic liquids that are compatible with each other, 1-butyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide is used as the ionic liquid and vinylidene fluoride-hexafluoropropylene copolymer is used as the elastic polymer in the ratio 0.78:0.22. The copolymer with this composition ratio exhibits elastic properties.

Q3: Are there any previous reports on conductive rubbers? What are the characteristic advantages of the present elastic conductors over other conductive rubbers?

A3: Carbon-nanotube-based conducting materials have been produced previously. Their conductivities are very low, typically 10^{-3}~10^{1} S/cm, as nanotubes that form bundles cannot be dispersed uniformly in polymer matrices. Since previous reports on materials with a conductivity of 10 S/cm did not provide any experimental data regarding the mechanical properties of these materials, one can say that the elastic conductors developed in this study are the world's first chemically stable, highly conductive elastomers. Furthermore, carbon nanotube/conducting polymer (polyaniline) composites have also been developed; however, these materials cannot be stretched. Reports have also been presented on rubbers filled with silver particles; however, silver is not a suitable material for since it is easily oxidized and suffers from problems related to electromigration. The best commercially available rubbers are those that are filled with carbon particles. They have a conductivity of 0.1 S/cm. Although this conductivity may be sufficient for antistatic sheets, it is insufficient to operate integrated circuits. Thanks to the highly conductive elastic conductors developed in this study, elastomers can be used in wirings in integrated circuits for the first time.

Q4: I am afraid that elastic conductors may be expensive since both ionic liquids and SWNTs are currently expensive….

A4: This is incorrect. The advantage of the present fabrication method using ionic liquids is that after the dispersion of SWNTs, the ionic liquids can be recovered quantitatively (99%) by Soxhlet extraction and can then be recycled for the next batch process. After the extraction of ionic liquids, the conductivity decreases, but it is still as high as 10 S/cm. It is expected that ionic liquids will be used as electrolytes for rechargeable batteries. Thereby, the commercialization of ionic liquids will result in a drastic reduction in their cost in the future.

Furthermore, the supergrowth method used to synthesize SWNTs is an extremely efficient method that can be used for large-volume production. Therefore, elastic conductors will be supplied as cost-competitive materials for large-area electronic applications.

Q5: Please comment on the reliability and stability of these conductors.

A5: In this study, SWNTs were uniformly dispersed as a chemically stable dopant in a vinylidene fluoride-hexafluoropropylene copolymer matrix, which is very stable in air. It was observed that the electrical and mechanical characteristics of the conductor did not deteriorate with time for the period of at least a year.

Q6: Please comment on the durability or mechanical robustness of the elastic conductors.

A6: In order to investigate the reversibility of an elastic conductor, its behavior was observed for several stretching cycles. The conductance was measured as a function of the number of uniaxial stretching cycles. It was observed that there was no significant change in conductance even after 4000 25%-stretching cycles, 500 50%-stretching cycles, 20~50 70%-stretching cycles, or 1~2 110%-stretching cycles. Similar to other stretchable materials, either conducting or nonconducting, elastic conductors exhibit irreversible mechanics after a certain number of stretching cycles. However, the new conductor developed in this study with a conductivity of 50 S/cm can be stretched to approximately 500 times its original size at a high level of strain (50%) without significant degradation in its properties. The feasibility of such a robust conductor has been demonstrated unambiguously for the first time by using a net-shaped structure with a PDMS coating.

Q7: What is the next step?

A7: One of the most important steps now is the further optimization of the electric and mechanical properties of elastic conductors. Another challenge is to develop cost-effective patterning methods such as printing processes that are needed to form fine wiring patterns for integrated circuits.

Q8: Have stretchable integrated circuits been reported previously? What is new about your approach in this study?

A8: Professor Sigurd Wagner, Princeton University, and his coworkers have performed pioneering work on stretchable electronics and have initiated the development of electronics using metal electrodes on rubber substrates. Subsequently, Professor John A. Rogers and his coworkers have embedded active components such as transistors and diodes in rubber sheets and integrated them with wavy metal wires by carefully controlling the strains in thin films. Their developed electrical circuits have high mechanical durability and show good electrical performances under stretching as all the circuit components are stretchable. On the other hand, as an alternative cost-effective approach, integrated circuits have been directly fabricated on plastic films and then mechanically processed to form perforated films with net-shaped structures, which serve as stretchable artificial skins. Net-shaped integrated circuits are flexible but have inelastic wirings; their mechanical robustness can be significantly improved by using elastic conductor wirings. In this approach, the fabricated ICs, which have a high electronic performance, can be stretched to 70% of their original size without any degradation in their mechanical or electronic properties;

therefore, more reliable operation of ICs can be expected. It is extremely important for the ICs to be mechanically robust in order to realize durable, conformable electronics.

Q9: What are your plans for the future?

A9: The team will attempt to demonstrate unique applications that can be realized if ICs can be mounted on curved surfaces. Organic transistor technologies are emerging and have been intensively studied to realize flexible displays and/or printed radio tags. However, there are many competing technologies that focus on these two specific applications. Furthermore, the competition with existing technologies is tough. As this new field is at a nascent stage, it is very important to explore all the various possible unique applications of this technology and to demonstrate their feasibility. The team plans to conduct strategic research activities on applications that cannot be achieved by conventional silicon-based electronics, namely electronic artificial skins, wearable electronics, and others.