In-situ Synthesis of Carbon Nanotube–Graphite Electronic Devices and Their Integrations onto Surfaces of Live Plants and Insects

Kyongsoo Lee,†‡ Jihun Park,†‡ Mi-Sun Lee,†‡ Joohee Kim,†‡ Byung Gwan Hyun,†‡ Dong Jun Kang,§ Kyungmin Na,⊥ Chang Young Lee,‡ Franklin Bien,⊥ and Jang-Ung Park†‡∥

†School of Materials Science and Engineering, Low-Dimensional Carbon Materials Research Center, Ulsan National Institute of Science and Technology (UNIST), Ulsan Metropolitan City, 689-798, Republic of Korea
‡Nano-Convergence Devices Research Group, School of Nano-Bioscience and Chemical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan Metropolitan City, 689-798, Republic of Korea
§Creative and Fundamental Research Division, Korea Electrotechnology Research Institute, Changwon, 642-120, Republic of Korea
⊥School of Electrical and Computer Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan Metropolitan City, 689-798, Republic of Korea

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ABSTRACT: Here we report an unconventional approach for the single-step synthesis of monolithically integrated electronic devices based on multidimensional carbon structures. Integrated arrays of field-effect transistors and sensors composed of carbon nanotube channels and graphitic electrodes and interconnects were formed directly from the synthesis. These fully integrated, all-carbon devices are highly flexible and can be transferred onto both planar and nonplanar substrates, including papers, clothes, and fingernails. Furthermore, the sensor network can be interfaced with inherent life forms in nature for monitoring environmental conditions. Examples of significant applications are the integration of the devices to live plants or insects for real-time, wireless sensing of toxic gases.

KEYWORDS: Flexible electronics, wearable electronics, nanobio interfaces, nano electronics, all-carbon electronics

Encoding functional information into nanoscale materials during chemical synthesis has been explored extensively over the past decade as the key to developing nanoelectronics with suggesting potentials beyond the limits of conventional Si electronics. Carbon nanostructures, such as one-dimensional carbon nanotubes, two-dimensional graphene, and three-dimensional graphite, exhibit exceptional intrinsic properties, such as high carrier mobility, high electrical and thermal conductivity, and superb mechanical flexibility. Also, their good adhesion to the surfaces of biomaterials, including cells or neurons, provides significant potential for the integrations of carbon-based electronics with biological systems. The atomic geometries of carbon modulate electronic band structures, and thus in situ synthesis of multidimensional carbon structures to encode electronic functionality, enables entire integrated carbon electronics in a chemical synthesis. As an example, we recently demonstrated the synthesis of monolithic devices composed of graphitic electrodes and graphene channels. Instead of graphene which has zero bandgap, carbon nanotubes that can exhibit semiconducting properties also are attractive as the channel part for high on–off ratio. Furthermore, this multidimensional carbon structure, based on graphitic electrodes and nanotube channels, can provide the advantages of good electrical contact and sufficient mechanical flexibility. However, this approach to synthesize entire integrated devices using graphite and nanotubes had not been studied previously. Thus, in this paper, we report an unconventional approach for the in situ synthesis of monolithically integrated electronic devices based on single-walled carbon nanotube (SWCNT) channels and graphitic electrodes. Integrated arrays of carbon nanotube transistors with graphitic electrodes and interconnects were formed directly by the in situ synthesis. After the synthesis, these devices were transferable onto a variety of substrates, and they were flexible, operating consistently even when they were bent with radii of curvature as small as ~100 μm. On the basis of these capabilities, we demonstrated the integration of the all-carbon devices to inherent life forms in nature. Technologies to interface electronic circuits, especially sensor networks that have capabilities of transferring information and power wirelessly, with living flora and fauna can benefit humankind by monitoring the conditions of the environment, including the detection of chemical weapons, pollution, and infections, etc. In addition, the implanted devices can function consistently as sensors even after the in vivo activities of animals and plants have stopped. Real-time gas sensor arrays on a leaf of a live plant (Dracaena sanderiana cv. Virens, as known as “lucky bamboo”) or on the epidermis of a live insect (Lucanus maculifemoratus dybowskyi parry, as known as “stag beetle”) for the detection of simulants of sarin nerve agent provide the application examples.

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Differences in the morphology and carbon solubility of catalysts can generate different dimensional geometries of carbon by chemical vapor deposition (CVD) method. Thus, we demonstrated that patterns of such catalytic metals enable the synthesis of multidimensional, monolithic structures of graphite-SWCNTs (in the forms of random networks or horizontally aligned arrays) in localized and selected pattern areas. For example, films of a Co catalyst, which have relatively high carbon solubility (∼0.9 wt % at ∼1320 °C),15 can produce layers of graphitic carbon based on sp2 bonding by segregation and precipitation of the carbon on the metal surface.16–18 Furthermore, the addition of Cu, which has very low carbon solubility (<0.0001 at. % at 1,000 °C),19,20 into the Co film can form Co–Cu alloys during the thermal CVD process, and the ratio of Cu to Co in the alloys can control the carbon solubility to modulate the thickness of the graphite.7,15 For comparison, the nanoparticles of a Fe catalyst can produce SWCNTs, another carbon allotropes based on sp2 bonded carbon atoms. This occurs by the precipitation of as-dissolved carbon and its successive crystallization in the form of a cylindrical network after reaching the solubility limit at high temperature (∼1000 °C).18,21

Figure 1a illustrates the catalyst patterns before the CVD synthesis. For the growth of graphite-SWCNTs (as random networks) hybrid structures, a Cu foil (thickness: 50 μm) covered by a sputtered SiO2 top layer (thickness: 300 nm) was used as the substrate. Co (thickness: 150 nm) and Cu (thickness: 150 nm) were deposited sequentially without breaking a vacuum as rectangular pads for the source/drain (S/D) electrodes of the FETs. Then, the thermal evaporation of a very thin Fe (thickness: 6 Å) layer prepared the catalyst patterns, and the left bottom inset shows the optical micrograph. These patterns were preannealed at 925 °C for 2 h prior to carbon growth, to form metal alloys by local diffusion and to form Fe nanoparticles by dewetting on the SiO2 surface (see Supporting Information, Figure S1). In situ synthesis of the graphite-SWCNTs was performed by flowing methane to the preannealed sample at 925 °C during the CVD process. After the synthesis and removal of the substrate and catalytic metals, the graphite–SWCNTs hybrid structure was transferred onto the 300 nm-thick SiO2 layer on a Si substrate (the top image of Figure 1b). Furthermore, graphite with horizontally aligned arrays of the SWCNTs, instead of the random network forms of the SWCNTs, can be synthesized by replacing the SiO2/Cu foil by a stable temperature (ST) cut quartz wafer. The right of Figure 1a and the bottom of Figure 1b present the catalyst pattern and the scanning electron microscope (SEM) image of the graphite-aligned SWCNTs hybrid structure, respectively. Figure 1c shows an atomic force microscopy (AFM) image of the area of the aligned SWCNTs, indicating that the average coverage was 1 ± 0.2 tube/μm. The alignment of the nanotubes is caused by preferential growth along certain crystallographic directions during the transition of the structure phase of quartz under annealing for an extended period of time.22,23 The Raman spectrum of the graphite region in Figure 1d (main panel) exhibits three characteristic bands (D peak ∼1350 cm⁻¹, G peak ∼1590 cm⁻¹, 2D peak ∼2680 cm⁻¹) and shows a predominant intensity of the G band compared to the 2D band, which indicates the presence of graphite.7,24 A left inset and two right insets of Figure 1d show the Raman spectrum of the SWCNTs and two-dimensional intensity maps of the G and 2D bands near the contact area between graphite and the horizontally aligned SWCNTs, respectively. The cross-sectional transmission electron microscope (TEM) images (see Supporting Information, Figure S2), as well as these mapping results (the right of Figure 1d), indicated that there was physical contact between the graphite and the SWCNTs without forming the covalent transformation of sp2 carbon. When graphite and SWCNTs were synthesized together inside a CVD chamber, the as-synthesized SWCNTs were in contact with the surface of the graphite at 925 °C, which provided

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**Figure 1.** In situ synthesis of SWCNTs–graphite structures using patterned metal catalyst films. (a) Schematic illustration of catalyst patterns for random network SWCNTs–graphite structure (left) and horizontal aligned SWCNTs–graphite structure (right). Scale bars, 100 μm. (b) Scanning electron microscope (SEM) images on two different types of SWCNT arrangements (top, random network SWCNTs–graphite structure; bottom, horizontally aligned SWCNTs–graphite). Scale bars: 20 μm. (c) Atomic force microscopy (AFM) image of the horizontally aligned SWCNTs that connect to an edge of graphite. The bottom inset shows step heights of the SWCNTs array. Scale bar: 2 μm. (d) Raman spectra (left) from the regions of graphite and SWCNTs (inset of left). Two-dimensional Raman intensity maps (right) of G (1520–1680 cm⁻¹) and 2D (2570–2780 cm⁻¹) bands in the region of SWCNTs–graphite contact. Scale bars, 10 μm.
clean, uncontaminated interfaces during the synthesis step. Although the junctions are not covalently bonded, the connections between the graphite and nanotubes formed at 925 °C are robust enough to withstand multiple steps of photolithography and wet processes.

The capability to tune the electrical properties of carbon through the synthetic control of structural dimensions provides a method for the rational design and synthesis of all-carbon electronics. As stated in previous report, the CVD-synthesized graphene films exhibit much lower sheet resistances than graphene or carbon nanotubes, and they also present negligible transconductance, similar to metals. These properties as well as the high flexibility and good contact properties with carbon nanotubes allow graphite to be a candidate for S/D electrodes in the carbon nanotube field-effect transistors (FETs). These FETs, graphitic S/D and the active channel of the percolating random network or aligned SWCNTs, were synthesized using the catalysts described in Figure 1, and their back-gate responses were characterized after they were transferred onto the 300 nm-thick SiO₂ on a Si wafer by removing the Cu foil and metal catalysts (see Supporting Information, Methods). S/D current (I₈) versus back-gate voltage (V₉) characterization of these FETs was performed at room temperature and in the ambient air. Figure 2a shows the electrical characteristics of the FET based on the random network SWCNTs, which exhibit p-type behavior, as expected. This FET presents an effective mobility of ∼90 cm²/V·s, calculated using a standard metal-oxide-semiconductor FET model. Mixtures of semiconducting and metallic nanotubes are synthesized during the CVD process, and the population of these metallic tubes results in the low on–off ratio of FET and negligible current saturation even at high drain voltages. Removing the metallic tubes or disconnecting metallic paths between source and drain to overcome the utility limitations represent next steps toward the future, high-performance devices. We investigated the electrical contact property at the interface between the SWCNT channel and graphite electrodes, as shown in the right of Figure 2a. This I–V graph showed a linear characteristic at room temperature, indicating no Schottky contact behavior. Figure 2b shows curves of the FET with the horizontally aligned SWCNTs channel. The SWCNTs array consists of ~1 tube/μm, and an effective device mobility of ~20 cm²/V·s was calculated using a parallel-plate model for capacitance (C) and the transfer curve according to μdev = (L/WCVдв)·(dI₈/dV₉). The characteristic of electrostatic capacitance coupling of the gate to the SWCNTs was critically important to the behavior of this device. The accurate capacitance model yielded a mobility of ~130 cm²/V·s in the linear regime. (Calculations of this gate capacitance are given in the Supporting Information). We speculate that exposing SWCNTs to the etchants during the transfer step can induce defects, thereby resulting in lower mobility than those reported previously. The number of semiconducting tubes was statistically greater than the number of metallic tubes, which suggests the possibility that only the semiconducting SWCNTs can exist in an array with no metallic tubes when the density of the aligned SWCNTs was reduced below the threshold density. In our experiments, a very low density of ~0.04 tube/μm was obtained by modulating the deposition condition to create lower density of the Fe nanoparticle catalyst. As shown in Figure 2c, this transistor had a high on–off ratio, exceeding ~10⁶ with negligible currents in the range of ~10⁻⁹ A for the off state. The mobility values calculated using the parallel-plate model and the accurate capacitance model were 3.2 and 264 cm²/V·s, respectively. The capacitance coupling of the aligned SWCNTs converges to the capacitance of the parallel-plate channel with identical geometry when the density is greater than inverse distance to the gate electrode (thickness of the gate dielectric). In contrast, the influence of capacitance coupling is more important when the density is much smaller than the inverse distance to the gate electrode. Figure S3, Supporting Information, shows the optical transmittance spectra of the synthesized SWCNTs and graphite, respectively. SWCNTs with the random networks or aligned arrays exhibit relatively high transmittances (greater than 95%) in the visible range (550 nm in light wavelength), and the transmittance of the graphite decreased as its thickness increased. For example, a thick graphite film with an average thickness of 150 nm has a transmittance of ~15%.

This synthesis approach facilitated the production of integrated, field-effect sensor arrays in which all components of the devices consisted of carbon (the random network SWCNTs as channels and graphite as S/D and interconnects). As shown in the left of Figure 3a, each block of the array possessed nine field-effect sensors with a single graphite common source and independent drains. One chip contained four of these blocks and had a total of 36 sensors. A 2 μm-thick SU8 passivation layer covered the graphite electrodes, and there were openings around the SWCNT channels. Molecules that were adsorbed on the surface of the SWCNTs modulate the resistance of the channel by donating or withdrawing electrons. This molecular doping effect and the subsequent changes in resistance enable the SWCNTs–graphite devices to operate as sensors. As a demonstration, we report the detection

![Figure 2](image-url)

**Figure 2.** Electrical characteristic of the in situ synthesized graphite-SWCNTs FETs. (a) Transfer (left, V₈ = −3 V) and output characteristics (middle, V₉ from 0 to −30 V in 10 V steps) using random network SWCNTs as the channel, and I–V curve (right) of the interface between the channel and two graphite electrodes. (b) Transfer (left, V₈ = −3 V) and output curves (right, V₉ from 0 to −30 V in 10 V steps) using the horizontally aligned SWCNTs as the channel. (c) Transfer (left, V₈ = −3 V) and output curves (middle, V₉ from 0 to −30 V in 10 V steps), and a SEM image (right) of the FET with extremely low density of aligned SWCNTs. Scale bar: 30 μm.
enable the discrimination of analyte mixtures under variable temperature, wind, etc. Our approach, which allows for the one-pot synthesis of a large array of nanotube sensors, thus presents a significant step forward in overcoming the current limitations of nanotube sensors. The hydrophobic nature and high elastic modulus of the SWCNTs–graphite hybrid structure enable entire, integrated sensor arrays in a free-standing form to float sustainably on water (the right of Figure 3a). By transferring the floating devices, the integrated sensor chip easily can be formed on various nonplanar substrates. For example, Figure 3b shows chips of the all-carbon device fitted onto the surfaces of a fingernail, a particulate mask (3M), a protective arm sleeve (DuPont, tychem C), an adhesive tape (3M, Scotch), and a sheet of newspaper.

For measurements of the transconductance modulation by the DMMP vapor, these floating device arrays were transferred onto a 300 nm-thick SiO2 dielectric layer on a highly doped p-type Si wafer as a gate. The transfer characteristics of these FETs were scanned by applying $V_d = -5$ V at room temperature. The signal measured is the change in normalized resistance, $\Delta R/R_0 = (R - R_0)/R_0$, where $R_0$ and $R$ are the resistance values before and during the DMMP exposure, respectively. Figure 3c presents the transfer curves (left) and the real-time signal of the sensor (right, $V_g = 0$ V) upon exposure to DMMP at concentrations of 5, 10, and 15 ppm. The transconductance and conductance in the p-type regime decreased when the concentration of DMMP was switched to higher values, and hence the signal ($\Delta R/R_0$) increased immediately in proportion to the concentration of DMMP. Charge transfer from the amine groups in DMMP to the p-type semiconducting SWCNTs reduces the hole density in the SWCNTs, thereby resulting in higher resistance of channel. Furthermore, the DMMP molecules that were physisorbed on the SWCNTs increase the contact resistance at the SWCNT–SWCNT junctions.

Flexible electronics represent an important application area that can be realized using the SWCNTs–graphite devices. For example, theoretical studies have reported that individual SWCNT can be sustainable without breakage as the bending-induced strain increases up to 30%. In comparison to metals, graphite also has the advantage of superb mechanical flexibility. The mechanical flexibility of the SWCNTs–graphite sensors was evaluated using bending and cyclic fatigue tests (Figure 4). For these investigations, the SWCNTs–graphite devices floating on water were transferred onto 1.4 μm-thick polyethylene terephthalate (PET) films, and these samples were wrapped onto various cylindrical supports with different curvatures (Figure 4a). The resistance of each sensor was measured by applying bias to S/D in flowing DMMP vapor. The bending-induced strain ($\varepsilon$) was estimated, according to $\varepsilon = \varepsilon_{\text{theory}}/R$, where $\varepsilon$ and $R$ are the thickness of the sample (including the thickness of the PET) and the radius of curvature, respectively (the left of Figure 4a). Figure 4b shows the relative difference in the resistance of the sensor as a function of $\varepsilon$. No significant change in the resistance occurred when the samples were bent to radii of curvature as small as 1 mm, and the sensors operated consistently without cracking. Also, these SWCNTs–graphite sensors can be bent further by transferring them onto cylindrical supports directly without the use of PET films. The removal of the PET decreases $\varepsilon_0$ and hence can result in a smaller $\varepsilon$. As an example, the DMMP gas sensors were transferred directly onto the curved surface of an optical fiber that had a radius of 100 μm, and then the changes
in resistance were determined in real time by changing the concentration of DMMP (Figure 4c). Although wrapping these devices around the fiber produced a much higher strain of \( \sim 14\% \), operation of the sensor was robust (the left of Figure 4c). Also, a fatigue test was conducted using a cyclic bending machine at a frequency of 1 Hz for the duration of 10 000 bending cycles. For this experiment, the SWCNTs–graphite devices that had been transferred onto an 80 \( \mu \)m-thick PET film were bent to radii of curvature as small as 1 cm, corresponding to a strain of \( \sim 0.8\% \). In this test, these SWCNTs–graphite devices endured 10 000 bending cycles without significant structural deformations or degradation of electrical performance (Figure 4d).

Health or environmental monitoring devices mounted on human skin are of great interest, and efforts to integrate diverse classes of electronic circuits and sensors directly with human skin or environmental monitoring devices are of great interest, and efforts to integrate diverse classes of electronic circuits and sensors directly with human skin or environmental monitoring devices are of great interest, and efforts to integrate diverse classes of electronic circuits and sensors directly with human skin or environmental monitoring devices are of great interest. 

**Figure 4.** Mechanical flexibility of the SWCNTs–graphite sensors. (a) Photographs of the sensors wrapped on various cylindrical supports with difference curvatures (left) and schematic image of the direction of the bending-induced strain in the sensor (right). Scale bars: 1 cm. (b) The relative difference in resistance as a function of bending radius (left) and as a function of bending-induced strain (right) of the SWCNTs–graphite devices wrapped on various cylindrical supports with different curvature. In the left graph, zero value of bending radius indicates the flat condition before bending. (c) Optical micrograph (left) of the SWCNTs–graphite sensors wrapped on an optical fiber with a radius of 100 \( \mu \)m and the normalized change of resistance upon exposure to DMMP vapor (right). Scale bar: 100 \( \mu \)m (d) The relative differences in resistance as a function of bending cycles under 10 000 cycles of bending-induced strain.

**Figure 5.** Molecular gating effects of SWCNTs FET as gas sensing application. (a) A Photograph (left, scale bar, 1 cm), an optical microscope image (right, scale bar, 50 \( \mu \)m), and the \( I–V \) characteristic (inset) of SWCNTs–graphite arrays transferred onto surface of a live leaf. (b) Real time sensing properties SWCNTs–graphite array at different concentrations of DMMP. (c) Photographs of SWCNTs–graphite arrays transferred onto surface of the insect. Scale bars: 1 cm. (d) Real-time sensing properties of SWCNTs–graphite structure onto an epidermis of insect at fixed (left) and different (right) concentration.
skin or organs have increased rapidly in recent years.\textsuperscript{45–50} For this type of approach, the potential concerns are the long-term safety of the human body and discomfort in everyday life.\textsuperscript{31} As an alternative strategy that avoids using the human body, the integrated electronics can be interfaced with living flora and fauna in nature to provide useful information, such as various environmental conditions, including temperature, humidity, and infections. This approach is especially promising for the rapid detection of chemical warfare agents or contaminants within devastated areas that are inaccessible by people. Also, the good adhesive property of the all-carbon nanostructures allows them to adhere directly onto the surfaces of organisms, in a conformal manner, via van der Waals forces alone.\textsuperscript{50}

As a demonstration of the device’s interface with nature’s life forms, the SWCNTs–graphite sensor array with structures shown in Figure 3a was transferred and laminated directly on the surface of a leaf of a live plant (\textit{D. sanderiana cv. Virenus}, also as known as “lucky bamboo”) for sensing DMMP vapor in air (Figure 5a). DMMP is used for producing soma (methylphosphonofluorid acid) and sarin (1,2,2-trimethylpropyl ester) nerve gases, and it also can be used as a simulant for sarin.\textsuperscript{57,58} The layout of this all-carbon device followed most of the topography of the leaf without generating any significant cracks in the SWCNTs–graphite structures, and we also observed negligible delamination of the device from the leaf even after 1 month (see Supporting Information, Figure S4).

An inset of Figure 5a presents the linear $I$–$V$ characteristic of the device, indicating that the Ohmic-like contact property between the SWCNTs channel and graphitic S/D was still preserved on the leaf. Figure 5b shows the real-time response of the sensor to the various concentrations of DMMP vapors in the atmosphere at room temperature. As DMMP vapor was injected, the sensing signal appeared immediately with the short response time of only about 5 s, and its intensity ($\Delta R/R_0$) increased almost linearly with the concentration of DMMP. Similarly, interfaces of all-carbon electronics can be formed with moving insects. For example, Figure 5c shows photographs of the SWCNTs–graphite sensor array adhering to the epidermis of a live stag beetle (\textit{L. maculifemoratus dybowskyi parry}). The transfer process of the device was performed while the insect was anesthetized (see Supporting Information, Methods), and we did not observe any abnormal behavior of the live insect after the anesthesia wore off, as shown in Movie S1, Supporting Information. Figure 5d shows real-time DMMP sensing results using the sensor array that was integrated onto the insect. And the sensing characteristics of the sensors on three different surfaces of SiO\textsubscript{2}, leaf, and insect are compared in Table S1, Supporting Information. At a given concentration, the magnitude of the signal ($\Delta R/R_0$) was consistent across the three different types of surfaces (SiO\textsubscript{2}, leaf, and insect epidermis). However, the noise level and the recovery time of the signal varied significantly, depending on the substrate. For example, the sensor on the leaf presented the noisiest response and the longest recovery time (a few minutes). We assume that this noise was caused by the difficulty of the probe’s tips making good contact with the graphitic interconnect pads on the leaf surface during the real-time measurement due to the softness and weakness of a nature of leaf. Furthermore, the recovery was found to be slightly dependent on the type of substrate. This dependency may arise from various mobile ions (such as K\textsuperscript{+}, Na\textsuperscript{+}, and Cl\textsuperscript{−}) in the water at the bottom of the epidermis of living entities. This effect was especially noticeable in the leaf, which had a water content that was greater than that of the insect.\textsuperscript{51,52} This influence of moisture on sensing characteristics was investigated using the sensor on the SiO\textsubscript{2} surface, by exposing the sensor to DMMP (5 ppm) in different air humidity (25% and 70% RH). As shown in Figure S5, Supporting Information, the noise level and recovery time increased with air humidity. Therefore, different moisture levels of environment can affect the noise and recovery time of the sensors. For example, stomata in the leaf allow gas exchange to produce relatively humid conditions around the sensor on the leaf, which can increase the noise and recovery time.

Next, we explored the inductively coupled functionalities of the SWCNTs–graphite sensor operating at radio frequency (RF) for monitoring environmental conditions wirelessly without power consumption.\textsuperscript{53–55} We demonstrated a sensor that had an electrical RLC resonant circuit that was composed of the resistive (R) random network SWCNTs channel with (capacitive (C)) graphitic S/D electrodes and metal planar inductive (L) coils as an antenna instead of graphitic interconnects. To investigate the performance of the sensor when it was integrated directly with a living insect, the wireless sensor was transferred onto the epidermis of a stag beetle (see Supporting Information, Figure S6). The inductive metal coils were designed and simulated to operate at resonance frequency of 400 MHz. Figure S6 presents the measured reflection of the wireless sensor attached to the epidermis of the stag beetle with a resonant frequency of ~400 MHz which was in good agreement with the simulated result. It also shows the RF responses of the wireless sensor when exposed to DMMP at 5, 10, and 15 ppm. The measured reflection value (Figure S11 parameter) at the resonance frequency, which is inversely proportional to the electrical resistance in the SWCNTs channel as the resistive element of the circuit, decreased as the concentration of DMMP increased (see Supporting Information, Methods). This tendency in correspondence with characteristics of the sensor array using a probe station enables the easier to use a wireless sensing system for monitoring environmental conditions.

In conclusion, the work presented here demonstrates the chemical synthesis of monolithic SWCNTs–graphite electronics and the formation of its interface with life forms in nature. This synthesis approach exhibits unique features compared with conventional Si electronics. Our in situ synthesis of the entirely integrated SWCNTs–graphite electronics presents the encoding of electronic functionalities by controlling the dimensions of the carbon nanostructures synthetically. Our approach also simplified the intensive fabrication processes of conventional Si electronics such as ion-implantation doping, annealing, deposition, etching, and so on. Furthermore, this all-carbon electronics demonstrated a superb mechanical flexibility and good adhesion to the nonplanar surfaces of biomaterials, which offers unique potential for wearable electronics and bioimplantable sensor devices. The integration of the SWCNTs–graphite devices to live plants and insects for the real-time sensing of toxic gases with in vivo studies, provided examples of the use of the all-carbon electronics. We believe that the capability to synthesize devices with one-dimensional and three-dimensional nanostructures indicates that there is substantial promise for such electronic devices in the future.
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