Molecular electron doping to single-walled carbon nanotubes and molybdenum disulfide monolayers

Kazuhiro Yoshida¹, Ryoto Yura¹ and Yoshiyuki Nonoguchi∗
Faculty of Materials Science and Engineering, Kyoto Institute of Technology, Kyoto 606-8585, Japan
¹ These authors contribute equally to this work.
∗ Author to whom any correspondence should be addressed.
E-mail: nonoguchi@kit.ac.jp
Keywords: chemical doping, carbon nanotubes, transition metal dichalcogenides, electron doping, n-type doping, electronics, thermoelectrics

Abstract
Carrier doping is an essential way to inject holes and electrons to electronic materials, which modulates their transport properties. While the substitution of heteroatoms essentially modulates the band structure of most semiconducting materials, chemical (molecular) doping can achieve relatively reliable carrier concentration modulation, particularly for nanocarbons and two-dimensional semiconductors. Compared to p-type counterparts, the stabilization of n-type carbon materials has been a challenge not only for basic science but also for various electronic device applications. This Mini-Review describes rational concepts for, and the results of, a stable n-type doping technique mainly for carbon nanotubes using molecular reactions and interactions. The stable n-type carbon nanotubes with controlled carrier concentration are implemented in complementary circuits and thermoelectric energy harvesters. The molecular and supramolecular n-type doping is not limited for carbon nanotubes, but is utilized in the fabrication of conducting transition metal dichalcogenides such as a molybdenum disulphide (MoS₂) monolayer.

1. Introduction

The carrier doping to nanomaterials including single-walled carbon nanotubes (SWCNTs) has been an active research field in the last 30 years. Particularly due to their large surface area, molecular adsorption has a strong influence on the electronic properties of nanocarbon materials. In the atmospheric environment, the adsorption of oxygen contributes to p-type conduction in nanocarbons such as SWCNTs and graphene [1]. The SWCNT films often exhibit p-type transport properties, and then switch to n-type when treated at high temperatures and under reduced pressure. For many applications, a methodology to fix the carrier polarity is required.

The carrier doping of is enabled by various injection ways including heteroatom insertion, and chemical/electrochemical oxidation/reduction. Nanocarbons as well as organic materials and two-dimensional transition metal dichalcogenides (TMDCs) are known to be doped by intermolecular charge transfer, called as molecular doping. The adsorption of carrier donors, such as metals and chemical molecules, is the first step in the molecular doping process. Intercalation of alkali metals between graphite interlayers is a well-known phenomenon within this concept. It is well known that the introduction of impurity atoms dopes materials, but the controlled introduction of impurity atoms into some robust materials, such as SWCNTs, has yet to be established. In this context, it is anticipated that molecular doping will be more adaptable to the injection of carriers into sturdy low-dimensional materials, ranging from nanocarbons to transition metal dichalcogenide nanosheets.

Within the molecular doping regime, we would like to emphasize that the efficiency of carrier injection relies on the conduction band (otherwise, lowest unoccupied molecular orbital, LUMO level) while the stability of doped states depends on charge neutrality. Additionally, molecular doping is dependent on the surface area of...
Representative charge transfer type compounds which successfully generate n-type SWCNTs are shown in figure 1. Seebeck coefficient is expressed as $\alpha = \frac{\Delta V}{\Delta T}$. The thermoelectric properties of SWCNTs have been actively investigated from the viewpoint of energy harvesting as well as condensed matter physics, and the transport mechanisms of single-wire and network thin films have already been reported [12]. In the networks, the temperature gradient is localized at the nanotube-nanotube contact, and the Seebeck effect at the contact is dependent on the electronic structure of the CNT [13]. Depending on the chiral angle of the graphene sheet, CNTs can be classified as semiconducting or metallic, and semiconducting CNT-enriched films show the huge Seebeck coefficient of up to about 2 mV K$^{-1}$ [8]. In general, peak power outputs are optimized by tuning the carrier concentration; in this context, continuous tuning from p-type to n-type by electrochemical doping of CNTs has been examined [14].

One more requirement is the module design for efficient thermoelectric power generation, where p-type and n-type components are implemented in series. Since the dawn of molecular electronics including carbon and organic electronics, however, n-type doping has been a significant challenge, due to air-instability along with difficulty in charge injection [15]. From the viewpoint of static chemical bonding theory, the positively charged carbons can be interpreted as carbocations (positively charged carbons) and carboanions (negatively charged carbons) delocalized in graphene sheets. This is based on the exchange of charge through sp$^2$ bonds, called \( \pi \)-conjugation. From a static point of view (figure 2), upon oxidation, carboanions are generated so that the structural arrangement of backbones does not change. On the other hand, carboanions are highly reactive to electron-withdrawing (oxidizing) agents such as oxygen, carbon dioxide, and water in atmosphere, since the reactive conformation could form upon electron injection (chemical reduction). The issue to be solved is the stabilization of such negatively charged carbons.

Considering above, the development of design principles for rational chemical doping is highly helpful for future electronic application based on SWCNTs and related materials. This Mini-Review introduces recent approaches to the n-type doping of SWCNTs and related nanomaterials such as transition metal dichalcogenides (TMDCs), particularly for field effect transistors and thermoelectric power generation applications. We first show that various dopants were proposed to n-dope SWCNTs and TMDCs, where guiding principals for both doping are quite similar. Then, we would like to mention that recent tremendous efforts have addressed the fine tuning of doped states and improved their stability for practical applications.

2. Chemical doping to form n-type SWCNTs

A plenty of investigations have been devoted for realizing the n-type molecular doping of SWCNTs. Representative charge transfer type compounds which successfully generate n-type SWCNTs are shown in figure 3.

![Figure 1. Representative applications of SWCNTs: (left) field effect transistors, and (right) thermoelectrics.](image-url)
2.1. Electron transfer-type dopants

When the Lewis base compounds, especially with high highest-occupied-molecular-orbital (HOMO) levels, are adsorbed onto SWCNTs, partial electron transfer, and charge separation could occur. Recent representative n-dopants are listed in Table 1. The addition of strong reducing agents (e.g. alkali metals such as potassium (K)) enables the n-type doping of SWCNTs [16], which is analogous to the charge transfer-mediated intercalation into graphite, so-called graphite intercalation compounds (GICs) [23]. Due to air-instability, unfortunately, this dopant is now substituted to organic base and reducing agents. Chronologically, polyethylene imine was used to efficiently convert p-type SWCNTs to their n-type form. This dopant was first examined for the construction of field effect transistors with individual SWCNTs [17]. This polymeric dopant has widely been applied for various applications.
negative charge on the SWCNT compensation. In the case of n-type SWCNTs, for example, an external positive ion
When a charge is acquired by doping, a substance with the opposite polarity is required for charge
3.1. A guiding principles for stabilization
3. Supramolecularly doped n-type SWCNTs
Table 1. Representative electron transfer-type dopants.

| Dopants                     | Type of doping                                 | References |
|-----------------------------|------------------------------------------------|------------|
| alkali metal (e.g. potassium) | a strong reducing agent                         | [16]       |
| polyethylene imine (PEI)    | donation                                        | [17]       |
| reduced benzyl viologen     | two-step reduction                              | [18]       |
| metallocene                  | a strong reducing agent high sublimability      | [19]       |
| amines (e.g. hydrazine)     | a tuneable reducing agent                       | [20, 21]  |
| phosphines                  | a tuneable reducing agent                       | [22]       |

investigations for the last two decades, and has been recognized as a standard method. Successful n-type
dopants, furthermore, include reduced benzyl viologen, and metallocene with high HOMO levels. Although
these materials are highly reactive in air, they offer excellent electron doping ability due to their high reduction
potentials (shallow HOMO levels). Various moderate and tuneable reducing agents based on amines and
phosphines were proposed to produce air-stable n-type SWCNTs [20–22], promoting many subsequent studies
on composite materials. The encapsulation of cobaltocene was reported to reliably promote n-type doping [24].
1, 2, 4, 5-Tetrakis(tetramethylguanidino)benzene (ttmgb) showed two electron transfer to SWCNT transistors,
leading to the extraction of pure n-type transport, rather than ambipolar [3]. Even if the dopants’ HOMO levels
are moderate, dopant encapsulation might improve n-type doping efficiency [25, 26]. Furthermore, weaker
electron donors were used to achieve n-type characteristics from SWCNT films, including neutral surfactants
(e.g. Pluronic PEG-type polymers, and polyvinylpyrrolidone (PVP)) [27], and simple electron-donating
polymers (e.g. poly(vinyl alcohol) and poly(vinyl acetate)) [28].

2.2. Hydrogen, hydride, and radical transfer-type dopants
The chemical reduction resulting in n-type doping is not limited in the electron transfer from high HOMO
compounds (table 2). Hydrogen and/or hydride (H+) transfer reagents are mostly successful for the reliable
n-type doping of SWCNTs. This reduction motif can be used widely in the electron transport chain in biological
systems (e.g. nicotinamide adenine dinucleotide NAD+/NADH redox couple for eukaryote). This reaction
system was promptly useful for the n-type doping of SWCNTs [29]. Furthermore, the derivatives of dimethyl-
dihydro-benzimidazole (DMBI) were found to efficiently produce air-stable SWCNTs and also organic
semiconductors/conductors. One of representative forms is 4-(2, 3-Dihydro-1, 3-dimethyl-1H-benzimidazol-
2-yl)-N,N-dimethylaniline, known as N-DMBI. The chemical reaction mechanism with N-DMBI is still
under investigation [30–32], while its doping ability can be widely used.
Organometallic dimer dopants were developed to efficiently dope nanocarbons as well as organic
semiconductors, similar to DMBI derivatives. They also launch hydrogen and/or hydride. Similar to these
dopants, various hydride reagents including triarylmethane derivatives are expected to work as efficient n-type
dopants for SWCNTs. Recently, highly reactive species such as organic radicals have been used for efficient
n-type doping. Fujigaya and colleagues utilized in situ generated pyridine (py)-boryl radicals to n-dope
SWCNTs [38].

3. Supramolecularly doped n-type SWCNTs
3.1. A guiding principles for stabilization
When a charge is acquired by doping, a substance with the opposite polarity is required for charge
compensation. In the case of n-type SWCNTs, for example, an external positive ion (cation) is introduced to the
negative charge on the SWCNT (figure 4). When alkali metals such as sodium and potassium are added to
neutral CNTs, as noted before, electron transfer occurs quickly and the CNTs exhibit n-type transport. In this
process, the metal ions that lose electrons are thought to form an ionic pair with the negatively charged CNTs. On the other hand, this n-type material is known to be easily oxidized by atmospheric species (oxygen, water, etc). This instability is attributed partly to the compatibility between the charges. In general, small ions are known to form ion pairs through Coulomb interactions (e.g. NaCl). Relatively large cations such as cesium ion and tetramethylammonium form stable complexes with relatively large anions such as iodine ion. In this process, the large ion pairs are stabilized by Coulomb interaction as well as dipole-dipole interaction, that is, the shape symmetry effect. This phenomenon is known as the hard-soft acid-base (HSAB) rule which is an empirical
ether-metal ion complexes

Nonoguchi, Kawai, and colleagues found that extremely delocalized supramolecular cations such as crown ether can be applied to the chemical doping of SWCNTs. Investigating the introduction of various cations, such as sodium ions and potassium ions, to form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether. Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether. Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether. Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether.

3.2. Anion-induced electron transfer

Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether. Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether. Cationic metal ions such as sodium ions and potassium ions form stable complexes with crown ethers. At the same time, the anions are detached from the cations and destabilized by the charge shielding of the crown ether.

Representatively, SWCNTs were soaked in ethanol solution containing sodium borohydride (NaBH₄) and 15-crown-5-ether, which are typical reducing salts, prior to thorough drying. The carrier polarity can be determined from the sign of the Seebeck coefficient. The raw SWCNT films gave a positive value indicates that they are p-type, and the crown ether and NaBH₄ alone are slightly doped. The addition of crown ether or NaBH₄ alone led to slight doping, but the materials gradually returned to the initial state under atmospheric conditions. On the other hand, the CNT film treated with both reagents showed extremely stable n-type characteristics under air (figure 5(d)). This result strongly supports the working hypothesis described above.

3.3. Monitoring doping progress

Tuning the carrier concentration by doping is essential for optimizing thermoelectric conversion as well as tuning the threshold voltage in field effect transistors/thin film transistors (TFTs). Tracking doping progress is important, and various ways for this have been proposed including electron spin resonance, x-ray photoelectron spectroscopy. Ultraviolet photoelectron yield spectroscopy was used to examine the Fermi level of doped

| Dopants                  | Type of doping                        | References |
|--------------------------|---------------------------------------|------------|
| reduced benzyl viologen  | two-step reduction                    | [44]       |
| cesium carbonate         | a strong base widely used              | [45]       |
| 15-crown-5 ether         | also in organic electronics            | [45]       |
| triphenyl phosphate      | stable and reversible                  | [46]       |
| polyethylene imine       | moderate electron donor                | [47]       |
| crown ether complexes    | anion induced electron                | [48]       |
|                          | transfer high air-stability            |            |

rule for ionic interactions in solution [39]. This concept is widely accepted in supramolecular science, and is considered to be applied to the chemical doping of SWCNTs. Investigating the introduction of various cations, Nonoguchi, Kawai, and colleagues found that extremely delocalized supramolecular cations such as crown ether-metal ion complexes (figure 5(b)) stabilized n-type SWCNTs [40].

Representatively, SWCNTs were soaked in ethanol solution containing sodium borohydride (NaBH₄) and 15-crown-5-ether, which are typical reducing salts, prior to thorough drying. The carrier polarity can be determined from the sign of the Seebeck coefficient. The raw SWCNT films gave a positive value indicates that they are p-type, and the crown ether and NaBH₄ alone are slightly doped. The addition of crown ether or NaBH₄ alone led to slight doping, but the materials gradually returned to the initial state under atmospheric conditions. On the other hand, the CNT film treated with both reagents showed extremely stable n-type characteristics under air (figure 5(d)). This result strongly supports the working hypothesis described above.

Such anion-induced electron transfer may be caused by the activation of anions according to the HSAB rule in addition to charge shielding. The Seebeck coefficient of CNTs with 15-crown-5 and various sodium salts showed that the efficiency of n-type doping varies with the size of the anion species (figure 5(f)). In particular, the efficiency of n-type doping is relatively high for small anions such as hydroxide ions (133 pm) and chloride ions (17.2 pm), which are small anions, showed relatively high n-type doping efficiency. In other words, large anions such as triflate (307 pm) can form relatively stable ion-pairs (complexes) with metal ions encapsulated in the crown, while small anions cannot form stable ion pairs, and are expected to induce anion-induced electron transfer.

Thermal stability was also examined for thermoelectrics application based on SWCNT sheets. When potassium hydroxide and benzo-18-crown were used as dopants, no significant degradation of any thermoelectric properties was observed for more than 700h (about one month), at 100 °C. A systematic dopant survey revealed supramolecular dopants with an aromatic structure show significant thermal stability, compared to small crown ether complexes.

3.3. Monitoring doping progress

Tuning the carrier concentration by doping is essential for optimizing thermoelectric conversion as well as tuning the threshold voltage in field effect transistors/thin film transistors (TFTs). Tracking doping progress is important, and various ways for this have been proposed including electron spin resonance, x-ray photoelectron spectroscopy. Ultraviolet photoelectron yield spectroscopy was used to examine the Fermi level of doped
unchanged even after 24 days of air exposure.

Most molecular dopants developed for nanocarbons and organic electronics are readily useful for the doping of TMDC thin layers and monolayers.

Inversely, controlled p-type doping can dramatically enhance PL derived from the exciton photoluminescence quantum yield, the controllability of chemical doping is important for this purpose.

In addition to electronic device applications, the doping is also important for elucidating optical response. Trion is a charged exciton (a electron-hole pair), and has attracted significant attention particularly for semiconductor quantum dots and SWCNTs. The tuneable chemical n-doping by cesium carbonate (Cs2CO3) revealed that, at room temperature, MoS2 monolayers were found to show trion photoluminescence (PL) at a region slightly low-shifted from the exciton photoluminescence [45]. Since heavy doping would spoil a photoluminescence quantum yield, the controllability of chemical doping is important for this purpose. Inversely, controlled p-type doping can dramatically enhance PL derived from the exciton [50].

We would like to show a representative approach to the stable doping of MoS2 monolayer and its full characterization. Miyata and colleagues have recently reported that MoS2 monolayer doped with the complexes of potassium hydroxide and crown ether shows air-stable, metallic conduction [48]. They found a dramatic increase in current density in MoS2 field effect transistors upon the supramolecular doping. Treatments with increased dopants led to a substantial increase in the off-current and in metallic gate dependence. Eventually, the region slightly low-shifted from the exciton photoluminescence 

4. Molecularly and supramolecularly doped n-type transition-metal dichalcogenide (TMDC) monolayers

Most molecular dopants developed for nanocarbons and organic electronics are readily useful for the doping of TMDC thin layers and monolayers (table 3). Representative, molybdenum disulfide (MoS2), known as a n-type semiconductor, was doped by organic reductants such as reduced benzyl viologen [44], leading to a substantial increase in current density in its field effect transistors. For the similar purpose, various chemical n-dopants were proposed for tuning the electronic properties of MoS2, including polyethylene imine [47], and triphenyl phosphine [46]. Electron doping with ammonia (NH3) was applied for the development of a MoS2-based NH3 detector, achieving the high sensitivity of ca. 300 ppb and the quantitatitivity at room temperature [49].

In addition to electronic device applications, the doping is also important for elucidating optical response. Trion is a charged exciton (an electron-hole pair), and has attracted significant attention particularly for semiconductor quantum dots and SWCNTs. The tuneable chemical n-doping by cesium carbonate (Cs2CO3) revealed that, at room temperature, MoS2 monolayers were found to show trion photoluminescence (PL) at a region slightly low-shifted from the exciton photoluminescence [45]. Since heavy doping would spoil a photoluminescence quantum yield, the controllability of chemical doping is important for this purpose. Inversely, controlled p-type doping can dramatically enhance PL derived from the exciton [50].

We would like to show a representative approach to the stable doping of MoS2 monolayer and its full characterization. Miyata and colleagues have recently reported that MoS2 monolayer doped with the complexes of potassium hydroxide and crown ether shows air-stable, metallic conduction [48]. They found a significant increase in current density in MoS2 field effect transistors upon the supramolecular doping. Treatments with increased dopants led to a substantial increase in the off-current and in metallic gate dependence. Eventually, the on-current reached ~100 μA for the sample treated with the 100 mM dopant solution, which represents an increase of approximately two orders of magnitude compared with the on-current of the untreated sample. Notably, the doped MoS2 FETs were highly stable in ambient air. The transfer curves remained nearly unchanged even after 24 days of air exposure (figure 7(c)).

The n-doped states of TMDCs can be tracked quantitatively by the measurements of optical properties that reflect electronic structures. Figure 7(f) shows the Raman spectra of monolayer MoS2 recorded before and after the doping treatments with different concentrations of the dopants (0.1–100 mM). The two characteristic Raman peaks denoted by E′ and A′, are attributed to the in-plane and out-of-plane vibration modes of monolayer MoS2, respectively [51]. The E′ mode (383 cm−1) varied depending very little on the dopant
concentration, while the $A_1'$ mode was downshifted by 6 cm$^{-1}$. This downshift is consistent with the earlier literature of electron doped MoS$_2$ with reduced benzyl viologen [44], suggesting that an increase in the electron concentration enhanced the electron–phonon interaction.

The photoluminescence (PL) spectroscopy revealed doping-enabled spectral change. PL measurements showed the emission peak from A exciton at 1.80 eV for the undoped MoS$_2$ (figure 7(g)). This PL peak was substantially suppressed by the n-doping treatments and was completely quenched at above a 1 mM crown-KOH concentration with a downshift of the peak to 1.72 eV. These PL shift and quenching can be explained by an increase of the emission from negatively charged trions as a result of the stable electron doping and the suppression of neutral exciton formation [52]. These optical responses are consistent with the transport measurement results for electron-doped monolayer MoS$_2$.

5. Outlook

Improving the air-stability of n-type SWCNTs and related materials has significantly advanced the understanding of physical properties as well as the applications in electronic devices and power generators. Behind such electronics applications, rational chemistry is required for tuning the electronic properties of nanocarbons and 2D semiconductors. We would like to emphasize that most chemical doping described here can be easily reproduced by anyone with commercially available dopants, and SWCNTs. The present doping procedure can also be applied to other nanocarbons (e.g. graphene, fullerene) and inorganic materials with large surface area [53]. Along with n-type doping, counterparts for p-type doping are also important for the development of reliable electronic devices. Such chemical doping has recently been utilized for elucidating the emerging optical properties of TMDCs [54, 55]. We hope that, in near future, the versatile molecular doping technology further promotes a variety of developments of emerging nano-molecular devices and their derived physical properties.

**Figure 7.** (a) Schematic and optical micrographs of the back-gated FET device. (b) Schematic model of the chemical doping using KOH/benzo-18-crown-6 for n-type doping. (c) and (d) The transfer (c) and output curves (d) of undoped and doped monolayer MoS$_2$ with different dopant concentrations from 0.1 to 100 mM. (e) Transfer characteristic curves of the device before and after doping. The doped device had been kept in air for 183 days. (f) and (g) Raman (f) and PL (g) spectra of undoped and doped monolayer MoS$_2$ with different dopant concentrations from 0.1 to 100 mM. Reproduced with permission [48]. Copyright 2021, The Royal Society of Chemistry.
Acknowledgments

The author thanks financial supports including JSPS KAKENHI grant number 19H02536, JST PRESTO grant number JPMJPR16R6, JST CREST grant number JPMJCR21Q1, and MEXT Leading Initiative for Excellent Young Researchers (LEADER).

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Yoshiyuki Nonoguchi https://orcid.org/0000-0002-4246-284X

References

[1] Bradley K, Jhi S H, Collins P G, Hone J, Cohen M L, Louie S G and Zettl A 2000 Phys. Rev. Lett. 85 4361
[2] Tan F W, Hirota J, Nonoguchi Y, Kishimoto S, Kataura H and Ohno Y 2021 Appl. Phys. Express 14 045002
[3] Schneider S, Brehmann M, Lorenz R, Hofstetter Y, Rother M, Sauter E, Zharnikov M, Vaynzof Y, Himmel H J and Zaumseil J 2018 ACS Nano 12 5849
[4] IRDS 2020 International Roadmap for Devices and Systems In (IEEE) https://irds.ieee.org/editions/2020
[5] Zhang J et al 2020 Adv. Mater. 32 2001093
[6] Takenobu T, Takano T, Shiraiishi M, Murakami Y, Ata M, Kataura H, Achiba Y and Iwasa Y 2003 Nat. Mater. 2 683
[7] Enomae T, Han Y H and Isogai A 2006 Nord. Pulp Pap. Res. J. 21 253
[8] Avery A D et al 2016 Nat. Energy 1 16053
[9] Komoto J, Goito C, Kawai T and Nonoguchi Y 2021 Appl. Phys. Lett. 118 261904
[10] Macleod B A et al 2017 Energy Environ. Sci. 10 21618
[11] Nakano M, Nakashima T, Kawai T and Nonoguchi Y 2017 Small 13 1700804
[12] Small J P, Perez K M and Kim P 2003 Phys. Rev. Lett. 91 256801
[13] Nakai Y, Honda K, Yanagi K, Kataura H, Kato T, Yamamoto T and Maniwa Y 2014 Appl. Phys. Express 7 025103
[14] Nonoguchi Y, Iihara Y, Ohashi K, Murayama T and Kawai T 2016 Adv. Mat. 26 15018
[15] Avery A D et al 2017 Adv. Funct. Mater. 19 2553
[16] Zhou C, Kong J, Yenilmez E and Dai H 2001 Science (80-. ). 290 1552
[17] Shim M, Javey A, Kan N W S and Dai H 2001 J. Am. Chem. Soc. 123 11512
[18] Kim S M et al 2009 J. Am. Chem. Soc. 131 327
[19] Li X et al 2014 Nano Lett. 14 3388
[20] Klinker C, Chen J, Afzali A and Avouris P 2005 Nano Lett. 5 555
[21] Mistry K S, Larsen B A, Bergeson J D, Barnes T M, Teeter G, Engtrakul C and Blackburn J I 2011 ACS Nano 5 3714
[22] Nonoguchi Y, Ohashi K, Kanazawa R, Ashiba K, Hata K, Nakamura T, Adachi C, Tanase T and Kawai T 2013 Nano Lett. 13 3344
[23] Otters D M and Rase HF 1966 Carbon N. Y. 4 125
[24] Fukumaru T, Fujigaya T and Nakashima N 2013 Sci. Rep. 3 7615
[25] Nakano M, Nakashima T, Kawai T and Nonoguchi Y 2012 Adv. Funct. Mater. 22 3021
[26] Enomae T, Han Y H and Isogai A 2006 Nord. Pulp Pap. Res. J. 21 253
[27] Avery A D et al 2017 Adv. Funct. Mater. 19 2553
[28] Zhou C, Kong J, Yenilmez E and Dai H 2001 Science (80-. ). 290 1552
[29] Shim M, Javey A, Kan N W S and Dai H 2001 J. Am. Chem. Soc. 123 11512
[30] Kim S M et al 2009 J. Am. Chem. Soc. 131 327
[31] Li X et al 2014 Nano Lett. 14 3388
[32] Klinker C, Chen J, Afzali A and Avouris P 2005 Nano Lett. 5 555
[33] Mistry K S, Larsen B A, Bergeson J D, Barnes T M, Teeter G, Engtrakul C and Blackburn J I 2011 ACS Nano 5 3714
[34] Nonoguchi Y, Ohashi K, Kanazawa R, Ashiba K, Hata K, Nakagawa T, Adachi C, Tanase T and Kawai T 2013 Sci. Rep. 3 3344
[35] Otters D M and Rase HF 1966 Carbon N. Y. 4 125
[36] Fukumaru T, Fujigaya T and Nakashima N 2013 Sci. Rep. 3 7615
[37] Nonoguchi Y, Iihara Y, Ohashi K, Murayama T and Kawai T 2016 Adv. Mat. 26 15018
[38] Avery A D et al 2017 Adv. Funct. Mater. 19 2553
[39] Zhou C, Kong J, Yenilmez E and Dai H 2001 Science (80-. ). 290 1552
[40] Shim M, Javey A, Kan N W S and Dai H 2001 J. Am. Chem. Soc. 123 11512
[41] Kim S M et al 2009 J. Am. Chem. Soc. 131 327
[42] Li X et al 2014 Nano Lett. 14 3388
[43] Klinker C, Chen J, Afzali A and Avouris P 2005 Nano Lett. 5 555
[44] Mistry K S, Larsen B A, Bergeson J D, Barnes T M, Teeter G, Engtrakul C and Blackburn J I 2011 ACS Nano 5 3714
[49] Lee K, Gatensby R, McEvoy N, Hallam T and Duesberg G S 2013 Adv. Mater. 25 6699
[50] Mouri S, Miyauchi Y and Matsuda K 2013 Nano Lett. 13 5944
[51] Lee C, Yan H, Brus L E, Heinz T F, Hone J and Ryu S 2010 ACS Nano 4 2695
[52] Mak K F, He K, Lee C, Lee G H, Hone J, Heinz T F and Shan J 2013 Nat. Mater. 12 207
[53] Nonoguchi Y, Kamikonya F, Ashiba K, Ohashi K and Kawai T 2017 Synth. Met. 225 93
[54] Amani M et al 2015 Science (80-. ). 350 1065
[55] Kiriya D and Lien D H 2022 Nano Express 3 034002