Oriented Nanowire Arrays with Phthalocyanine – C$_{60}$ Multi-Heterojunctions

Masaki Nobuoka, Koshi Kamiya, Shugo Sakaguchi, Akira Idesaki, Tetsuya Yamaki, Tsuneaki Sakurai, and Shu Seki*

1 Department of Molecu lar Engineering, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8510, Japan.
2 Department of Advanced Functional Materials Research, National Institutes for Quantum and Radiological Science and Technology (QST), Takasaki, Gunma 370-1292, Japan
3 Faculty of Molecular Chemistry and Engineering, Kyoto Institute of Technology, Sakyo-ku, Kyoto 606-8585, Japan.
E-mail: seki@moleng.kyoto-u.ac.jp

One dimensional nanowires systems with programmed multi-heterojunction along their axes have been presumed as an ideal nanomaterials platform for quantum confinements exhibiting novel electronic/photonic functions. Herein we have successfully produced free-standing nanowires with multi-heterojunctions of which spatial alignments are perfectly under control on a substrate by a facile protocol referred to as Single Particle Triggered Linear Polymerization method. Uniform nanowires were well-vertically aligned on substrates with tightly bound bases, and represented by the sequential bottom-up of ~ 10 nano-segments from copper phthalocyanine and Buckminster fullerene molecules. Efficient polymerization/crosslinking reactions with high enough $G$ values of 20-40 (100 eV)$^{-1}$ were rationalize the formation of the nano-segments with significant changes in their radial thickness. Although the released energy density by the employed high energy charged particle was extremely high, which is presumed from the value of linear energy transfer of $1 - 1.4 \times 10^3$ eV nm$^{-1}$, however electronic and Raman spectroscopies confirmed clearly that the nano-segments in nanowires reflected well opto-electronic characteristics of molecules at least the outer boundaries, suggesting the future application of the present multi-heterojunction systems as magneto-optical nanomaterials. We are able to make our own choices of the molecules with designed electronic states, and program them to 0-1 dimensional nanomaterials with sequential connection along a direction by the present technique.

Keywords: nanowire, high-energy particle, heterojunction, solid-state polymerization, free-standing

1. Introduction

Dot, wire, and plane-like structures of metals/semiconductor materials with nm-sizes have been attracted many attentions in view of their deserving as interesting platforms for quantum confinements [1, 2]. Single-nm scaled structures of the above 0-2 dimensional systems have been predicted as prerequisite for giving discrete energy levels of electrons, spins, or the other elementary excitations, and their deviations in sizes are crucial for recognizing outputs from the systems clearly represented by quantum confinements [3]. 2D quantum well systems with heterostructures have been widely investigated as a new class of materials and devices exhibiting novel electronic and photonic functions till date. Since the last decade, 1D nanowire systems have been developed with hetero-interfaces of coaxial core-shell manners

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In particular, exciton confinements in the quantum well exhibited efficient amplification of light output from the structures and lasing of the systems [6]. The low-dimensional 1D nature of nanowires are, however, not reflected by the hetero-interface of the “core-shell” structure: an extension of 2D quantum well structures embedding onto the surfaces of 1D nanowires.

Quantum confinement effects become explicit in the lower dimensional systems of quantum dot and/or quantum wires where structural boundaries, and hence the potentials define the density of states more discretely in phase space [7]. Resulting unique properties from heterojunctions among low dimensional quantum dots/nanowires are widespread over the above photonic applications. For instance, electron injection into heterojunction structure of semiconductor quantum dots is affected significantly by the interplay of spin and repulsive Coulombic interaction between two adjacent electrons. By tuning the sizes of quantum dots, hence Coulombic interaction, the interplay leads non-magnetic metallic – antiferromagnetic Mott insulator transition of the system [8, 9]. Upon light excitation of the heterojunction systems, photogenerated excitons confined in two adjacent quantum dots interact with each other, resulting biexciton states predicted to have a significant increase in their binding energy [10, 11].

To elucidate these unique properties originated from quantum confinements, spatial alignment of quantum dots/quantum wires is necessary for statistical analysis because electrical conductivity and/or binding energy of excitons can only be detected by unidirectional electron transport in their translational motion or light output under modulated external magnetic field along a direction [12, 13]. This has been the case making it hard to explore quantum confinement effects in low dimensional nanostructures.

In contrast to the progressive studies on inorganic nanowires, macromolecular systems as well as supramolecular polymerization have been the center for the 1D nanostructure formation based on organic molecules that enable us to embed functionalities on their surfaces by chemical processes [14-16]. Herein polymerization reactions and/or supramolecular interactions limit the resulting 1D structure of the systems, and their functions have been often in debates after formation of the structure. In addition, our “STLiP” technique allows us to fabricate 1D structure from a variety of small organic molecules with designated optoelectronic properties [17-19].

In STLiP protocol, high energy charged particle is employed as a reaction source, and injected into the condensed phases of organic molecules. The released energy from a particle along its trajectory is transferred efficiently onto the molecules, giving reactive intermediated to promote polymerization reactions as well as crosslinking reactions in a confined cylindrical small spatial area [20-22]. The molecules included in the area are immobilized with a considerable increase in their molecular weight, remaining in the condensed phases after successive sublimation processes. The length of nanowires reflects perfectly the initial thickness of the films because of the orthogonal trajectory of a particle with negligible change in its momentum against the substrate supporting the films [23, 24]. This also define explicitly the alignment of nanowires as orthogonal to the substrate. One principle requisite for STLiP protocol is to facilitate efficient polymerization reactions of the target organic molecules; we can make a free choice to satisfy this requirement in a variety of organic compounds.

We report on alternating heterojunction nanowires using STLiP technique. Distinct nano-segments composed of copper phthalocyanine (CuPc) and C60 were clearly visualized and adjoined in one nanowire, confirmed by elemental analysis and representative optical properties of the nanowires.
molecules. As demonstrated herein, we can program multi-heterojunction structures in 1D nm-sized cylindrical spaces from any organic molecules and control perfectly their alignments with an interplay of free-standing nature and extraordinarily high aspect ratio, which will be powerful candidates as future structural optical/electronic 1D nanomaterials.

2. Experimental

2.1. Chemicals

Both Buckminster fullerene 60 (C60) and copper(II) phthalocyanine (CuPc) were purchased from Tokyo Chemical Industry Co. Ltd. and used without further purification.

2.2. Nanowire fabrication and observation

Si and quartz substrates were cut into 1.5 cm² and 1.0 cm² square, respectively, sonicated in 2-propanol, dried, and treated with O₂ plasma prior to the use by VACUUM DEVICE Ltd. model PIB-20 ion bombarder. C60 and CuPc were deposited on the substrate in a vacuum at a rate of 0.2–0.4 Å s⁻¹ by using Kenix model KXV-250. The thickness of the films was evaluated by a Bruker Co. model Multimode 8 atomic force microscopy (AFM). 450 MeV ¹²⁹Xe²⁺ particles were generated from a cyclotron accelerator at National Institutes for Quantum and Radiological Science and Technology, Takasaki Advanced Radiation Research Institute. The prepared thin films were exposed to the above ion beam in a vacuum chamber (< 1×10⁻⁴ Pa). The number of incident particles was controlled at 10¹¹–10¹² particles cm⁻² to prevent severe overlapping of the ion tracks. Then, the irradiated films were further cut into small pieces, and developed by sublimation of the unreacted area using JEOL Ltd. model JFE-400 vacuum evaporator (< 1×10⁻³ Pa). The sublimation temperature was measured directly with a thermocouple on a tungsten board on which the substrate/samples were placed. The sizes and shapes of the isolated nanowires were characterized by using JEOL Ltd. model JSM-7001F Scanning Electron Microscope (SEM).

2.3. Spectroscopy measurements

Energy Dispersive X-ray spectroscopy (EDX) spectrum was measured on HITACHI Ltd. model Regulus 8220 SEM, equipped with HORIBA. Ltd. model X-MaxN80 011 silicon drift x-ray detector. Electronic absorption spectra were recorded on JASCO V-570 spectrometer. Raman spectra were measured on JASCO NRS-4100 spectrometer.

3. Results and Discussion

We have chosen two representative p/n type organic molecules as the target: CuPc and C60, respectively. STLiP protocol was applied for
multiple Layer-by-Layer (LbL) films of these compounds. CuPc has a planner molecular core with delocalized π-conjugated system, facilitating molecular stacking through π–π interaction, often giving columnar structures which have been demonstrated by their characteristic condensed phases of anisotropic discotic liquid crystalline phases [25]. In contrast the shape of C_{60} is spherical and numerous previous works have been focusing particularly onto formation of 1-D structure by polymerizing 0D C_{60} molecules [26]. C_{60}-based 1D nanowire formation was previously reported [27], in contrast, this is the first report on 1D nanostructures with heterojunctions between anisotropic disk-shaped 2D molecules and isotropic spherical 0D molecules. Fig. 1 is schematic illustration of STLiP technique employed in this work represented by three simple steps: fabrication of target LbL organic films of successive vacuum deposition of 10 layers of CuPc and C_{60} (CuPc–C_{60}) in total at 200 nm thick, irradiation of high energy particles passing through the target, sublimation of unreacted molecule for removal leading to free-standing nanowires on the surfaces (all-dry process).

Swift heavy charged particles of 450 MeV \textsuperscript{129}Xe\textsuperscript{23+} were irradiated to the LbL film in a vacuum chamber (<10^{-4} Pa) at the fluence of \(1 \times 10^{11} - 1 \times 10^{12}\) cm\(^{-2}\), followed by isolation of resulting nanowires by the dry process. Solvent-based wet-development processes are applicable in this case to isolate the nanowires on the substrate by dissolving unreacted parts of the films: this is the common protocol not only in the present nanowire formation but also in nanolithography processes [28]. The wet process, however, causes significant impacts on the morphology of nanowires via strong dissolution effects of molecules and surface tension of solvents themselves, which often leads the nanowires knocked-down on the substrate being no longer free-standing [19, 27]. Besides, wet process is unapplicable to the molecular systems exhibiting the lower solubility against the solvents employed with low enough boiling points and viscosity considering the successive drying of the system. The present all-dry process needs no solvents, where we can address all the issues raised in wet processes with minimized impacts on the morphology and alignments of nanowires [19]. We set temperatures at \(\sim 560\) K for the sublimation of C_{60} and CuPc in LbL films under vacuum (<10\(^{5}\) Pa). The sublimation temperature of mono-layer C_{60} or CuPc as \(\sim 560\) and \(\sim 480\) K, respectively. The equivalent sublimation temperatures of both compounds with small mismatch of \(\sim 80\) K is advantageous for the sublimation process of LbL binary molecular system, because the large mismatch tends to cause selective vaporization of one component with the lower sublimation temperature, leading to accelerated vaporization of the component giving the bubbles in underlayers and hence collapsing of the structures.

Bi- or multi-layered polymer films gave successfully multi-segment polymer nanowires by single particle nanofabrication technique through efficient crosslinking reactions and gelation promoted in each polymer layer [19, 29, 30]. Wet process was only the choice for isolation (development) of the multi-segment nanowires via dissolution of uncrosslinked polymer fractions, and 2D images of nanowires lying on the substrate were clearly visualized in the case. Pristine C_{60} as well as unsubstituted CuPc are both showing low solubility against most of all solvents, thus all-dry process is the best for efficient removal of unreacted parts of molecules. Resulted nanowires isolated by the process are clearly visualized in Fig. 2 as SEM images with high enough contrast reflecting encapsulation of Cu only in CuPc-based segments. Note that all the wires are free-standing on the substrate in spite of their overwhelming aspect ratio > 30; this is in striking contrast to the conventional nanolithography techniques not to realize free-standing nanostructures with high aspect ratio of \(\sim 10\) even with development process using super critical fluids [31]. It is also clear that the length of nanowires is uniform completely, which reflects well the initial total thickness of LbL films. Given

Fig. 3. EDX spectrum of CuPc–C_{60} nanowires on Si substrates. Nanowires were fabricated by irradiation with 450 MeV \textsuperscript{129}Xe\textsuperscript{23+} particles at the fluence of \(1.0 \times 10^{13}\) cm\(^{-2}\), followed dry process development. The electron acceleration voltage was 5 kV. The peak of Cu can be confirmed.

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molecular stacking through delocalized compounds. CuPc has a planner molecular core with phases of anisotropic discotic liquid crystalline demonstrated by their characteristic condensed chamber (<10^{-4} \text{ Pa}) at the fluence of 1\times10^{11}–1\times10^{12} cm^{-2}, followed by isolation of resulting nanowires on the substrate by dissolving unreacted processes are applicable in this case to isolate the multiple Layer-by-Layer (LbL) films of these polymerizing 0D C_{60} molecules [26]. C_{60}-based 1D particularly onto formation of 1-3D structure by technique employed in this work represented by molecules. Fig. 1 is schematic illustration of STLiP shaped 2D molecules and isotropic spherical 0D contrast, this is the first report on 1D nanostructures.

that the particle trajectories are perfectly orthogonal to the substrate plane and distribute randomly, the top-view images in Fig. 2 confirm well isolation of nanowires free from bundled structures upon fluence of particles < \sim 10^{11} \text{ cm}^2.

Clear contrast between each segment in the SEM images is also helpful to recognize the components due to electron-rich Cu incorporation in CuPc segment (bright tone) and electron-deficient all carbon segment (dark), and the significant changes in the radial thickness (cross-sectional size) is also visualized in these images. The efficiency of the cross-linking reaction depends strongly on materials against swift heavy ion irradiation, presumably showing significantly higher value in C_{60} than CuPc because of efficient neutral radical mediated chain reactions. This is the case giving the thicker radial thickness of segment even in one single isolated nanowire with multi-segments.

The radial thickness of nanowire can be theoretically accessible in terms of deposited energy density in an ion track by swift heavy ions. Given that simple polymerization/crosslinking reactions proceed at boundary surface of a nanowire, it is necessary to induce one crosslinking point per one polymer unit for macromolecular gelation, hence perfect immobilization of organic molecules. Radial size ($r$) of a nanowire is derived from requisite density of crosslinks which is presumed to be correlate linearly to deposited energy density within an ion track. The correlation can be given by crosslinking efficiency $G$ (number of crosslinks produced per 100 eV absorbed energy by an organic medium), and thus $r$ is represented by:

$$ r^2 = \frac{LET \cdot G \cdot M}{400 \pi d N_A} \ln\left(\frac{r_p}{r_c}\right)^{-1} \left(1\right), $$

where $M$, $d$, and $N_A$ are molecular weight, density of the target material, and Avogadro’s number, respectively. $r_c$ and $r_p$ are radial regimes of energy deposition area referred to as “core” and “penumbra”, determined respectively by the momentum of an incident particle. The former is defined by the region where energy is directly received by the target matter from a particle passing through, and the latter is the region where the energy was deposited by the first knocked-out electrons via ionization process caused by an incident particle: according to equipartition theorem the total energy deposited in the “core” or “penumbra” regions is well-branched each other. The values of Linear Energy Transfer (LET) are calculated with density of respective molecules in condensed phases derived from single crystal structures of C_{60} and CuPc, giving 14300 eV nm^{-1} and 10000 eV nm^{-1}, respectively for 450 MeV \^{129}Xe^{3+} particle. Polymerization reactions of C_{60} molecules have been of interests and reported in not only in solution but also in condensed phases. The reactions occur at multiple cites of spherical surface of a C_{60} molecule, and isotropic growth of polymerized chains [27]; this is advantageous to promote crosslinking reactions of resulting polymer chains, and reflected by the unusually high $G$ value of polymerization/crosslinking reaction in C_{60} as 35.3 (100 eV)^{-1}. In

![Fig. 4. Electronic absorption spectra of (a) pristine films and (b) nanowires ((blue) CuPc, (black) C_{60}, and (red) CuPc–C_{60}). The film of CuPc or C_{60} was prepared by depositing them on quartz substrates at 100 nm thick respectively. The nanowires were fabricated by irradiation with 450 MeV \^{129}Xe^{3+} particles at the fluence of 5.0 \times10^{11} \text{ cm}^{-2}, followed by dry process development.](image)
contrast, a CuPc molecule has heterocyclic structure similar to tetraphenylporphyrin (TPP) which shows relatively the lower $G$ value of 25.7 (100 eV)$^{-1}$ even with introduction of reactive groups in their periphery [32]; this is the case giving the smaller $r$ visualized for segments based on CuPc in Fig. 2.

Major contribution from CuPc molecules to the thinner segments was confirmed by EDX spectrometry with characteristic X-rays emission from Cu as an index (Fig. 3). The average length of the present free-standing nanowires was around 200 nm and the segments of CuPc distribute in depth of 10-200 nm. X-rays emission from the underlayers is crucial to confirm the presence of Cu atom in the segment, and thus EDX analysis with electron accelerated at 5 keV was employed in the present case rather than XPS: the former we can expect the deeper penetration length up to ~ 400 nm [33], covering entire length of nanowires in contrast to the higher selectivity for surface atoms in XPS measurements. The spectra is shown in Fig. 3, confirming the presence of Cu in the present free-standing nanowire systems.

The estimated energy density in an ion track reaches up to $>1$ keV nm$^{-1}$ at the center core, and this is high enough to cause severe damage in chemical structure of organic molecules. Preserving the molecular structures of both CuPc and C$_{60}$ was examined by electronic absorption as well as Raman spectroscopies. Nanowires could be also formed on transparent quartz substrates, and the free-standing nanowires on SiO$_2$ were used for above optical spectroscopies with films of pristine CuPc or C$_{60}$ at 100 nm thick as references. From the absorption spectra, it can be seen that the absorption spectra of the C$_{60}$ thin film [34] and the CuPc thin film [35] are almost the same as those in the literature, respectively, and that the spectra of the LbL films are the sum of these spectra (Fig. 4a). The broad spectrum was observed in Fig. 4b for single-segment nanowires based on C with weak signature of near-UV characteristic peaks of C$_{60}$. It is noteworthy that Q-bands electronic absorption at 620 and 690 nm, characteristic of phthalocyanine rings, is evident as a differentiate in spectra from multi-segment nanowires to C$_{60}$ single-segment C$_{60}$ one. The relative peak intensity between C$_{60}$ characteristic absorption bands to the Q bands of CuPc in nanowires is lower significantly than that of a LbL film before irradiation, which is due to the dramatic change in the radial thickness segments of C$_{60}$ and CuPc nanowires: the latter is significantly small, impacting more in the relative amounts of molecules in the volume.

Raman spectroscopy is a powerful tool to detect vibrational modes specific to the molecules with extremely high sensitivity [36], and thus used for the detection of the modes in CuPc–C$_{60}$ nanowires. The reference Raman spectra of pristine C$_{60}$ and CuPc films is displayed in Fig. 5(a) and (b) respectively. The characteristic peaks of specific vibrational modes are also indicated in Fig. 5(a) and (b). A peak at 1467 cm$^{-1}$ is characterized by a symmetric vibrational mode of type $A_{1g}$ [37], and the CuPc peaks at 1341 and 1467 cm$^{-1}$ can be assigned to symmetric and antisymmetric vibrations, respectively, of $A_{1g}$ modes [38]. The characteristic peaks were observed clearly in the nanowires with high enough resolution. This is suggestive of the cage structure of C$_{60}$ and the planar conjugated ring
structure of CuPc preserving in the nanowires after high energy charged particle irradiation and even after subsequent sublimation processes at high temperature. In contrast the high frequency peak of CuPc becomes broad significantly in the spectrum recorded for nanowires, which may be due to the denaturation of CuPc during Raman spectroscopy measurement with high extinction coefficient for the excitation light source at 532 nm. Chemical post-functionalization of polymer-based nanowires has been realized via active reaction cites on their surfaces [39], and the presence of CuPc ring structures as well as $C_{60}$ cages can be utilized as bridgeheads for the subsequent modification of the present nanowire systems with maximized active surfaces exposed by the free-standing nature.

Conclusion

Multi-heterojunction nanowires of p/n type organic semiconductor molecules were successfully fabricated by STLiP method applied for LbL films of binary organic molecules in their condensed phases: a unique protocol to produce programmed 1D nanostructures. The nanowires were supported with firm basis on a substrate, holding their vertical alignment. The length of the nanowires was uniform reflecting trajectory of a high energy particle; an energy source of chemical reactions to form the nanowire. In addition, the spatial distribution of nanowires were consistent with the hitting points by the particle orthogonally injected into the thin solid films of the molecules, visualizing well the particle trajectories with high spatial resolution. Nanowires composed of sequential multi-segments of $C_{60}$ and CuPc were confirmed using not only SEM images but also electronic absorption and/or Raman spectroscopy techniques. In our STLiP method, multi-heterojunction nanowires can be fabricated simply by irradiating ion beams to LbL films of organic molecules upon our free choices without designing any complicated chemical reactions/physical deposition in conventional organic/inorganic 1D nanostructure fabrication processes; this is a clear advantage of the present STLiP method. Directional order of systems with heterojunctions is a primary requisite for their practical use in device structures because flow of excited energy/charges is expected to be under controlled in the devices, unlikely to the exceptional cases of bulk heterojunctions in solar cells. In this study, we have established successfully a facile method allowing us to arrange the nanowires macroscopically with precisely programmed 0D nanostructures.

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References

1. E. Roduner, Chem. Soc. Rev., 35 (2006) 583.
2. V. V. Pokropivny and V. V. Skorokhod, Mater. Sci. Eng. C, 27, (2007) 990.
3. A. D. Yoffe, Adv. Phys., 51 (2002) 799.
4. O. Hayden, A. B. Greytak, and D. C. Bell, Adv. Mater., 17 (2005) 701.
5. B. Tian, X. Zheng, T. J. Kempa, Y. Fang, N. Yu, G. Yu, J. Huang, and C. M. Lieber, Nature, 449 (2007) 885.
6. D. Saxena, N. Jiang, X. Yuan, S. Mokkapati, Y. Guo, H. H. Tan, and C. Jagadish, Nano Lett., 16 (2016) 5080.
7. M. Fox and R. Ispasoiu, “Springer Handbook of Electronic and Photonic Materials”, S. Kasap, and P. Capper, Eds., Springer, Cham 2017, Ch. 40, pp. 1037–1057.
8. R. Ugajin, J. Appl. Phys. 76 (1994) 2833.
9. S. Kuman and V. Tripathi, Phys. Rev. B, 102 (2020) 235147.
10. H. Gotoh, H. Kamada, and T. Saitoh, Appl. Phys. Lett., 85 (2004) 3480.
11. X. Xu, D. A. Williams, and J. R. A. Cleaver, Appl. Phys. Lett., 86 (2005) 012103.
12. M. T. Björk, C. Thelander, A. E. Hansen, L. E. Jensen, M. Larsson, L. R. Wallenberg, and L. Samuelson, Nano Lett., 4 (2004) 1621.
13. Z. X. Koong, G. B. Garcia, R. Proux, D. Dalacu, P. Poole, and B. D. Gerardot, Phys. Rev. Appl., 14 (2020) 034011.
14. A. P. H. J. Schenning and E. W. Meijer, Chem. Commun., 26 (2005) 3245.
15. F. J. M. Hoeben, P. Jonkheijm, E. W. Meijer, and A. P. H. Schenning, Chem. Rev., 105 (2005) 1491.
16. S. Yagai, Y. Kitamoto, S. Datta, and B. Adhikari, Acc. Chem. Res., 52 (2019) 1325.
17. Y. Takeshita, T. Sakurai, A. Asano, K. Takano, M. Omichi, M. Sugimoto, and S. Seki, Adv.
18. A. Horio, T. Sakurai, G. B. V. S. Lakshmi, D. K. Avasthi, M. Sugimoto, T. Yamaki, and S. Seki, Nanoscale, 8 (2016) 14925.
19. S. Sakaguchi, K. Kamiya, T. Sakurai, and S. Seki, Quantum Beam Sci., 4 (2020) 7.
20. S. Seki, K. Maeda, S. Tagawa, H. Kudoh, M. Sugimoto, Y. Morita, and H. Shibata, Adv. Mater., 13 (2001) 1663.
21. S. Seki, S. Tsukuda, K. Maeda, Y. Matsui, A. Saeki, and S. Tagawa, Phys. Rev. B, 70 (2004) 144203.
22. S. Seki, T. Sakurai, M. Omichi, A. Saeki, and D. Sakamaki, “High-Energy Charged Particles Their Chemistry and Use as Versatile Tools for Nanofabrication”, Springer, Tokyo, 2015, DOI: 10.1007/978-4-431-55684-8
23. A. Chatterjee and J. L. Magee, J. Phys. Chem., 84 (1980) 3537.
24. S. Seki, S. Tsukuda, S. Tagawa, and M. Sugimoto, Macromolecules, 39 (2006) 7446.
25. T. Wöhrle, I. Wurzbach, J. Kirres, A. Kostidou, N. Kapernaum, J. Litterscheidt, J. C. Haenle, P. Staffeld, A. Baro, F. Giesselmann, and S. Laschat, Chem. Rev., 116 (2016) 1139.
26. F. Giacalone and N. Martin, Chem. Rev., 106 (2006) 5136.
27. Y. Maeyoshi, A. Saeki, S. Suwa, M. Omichi, H. Marui, A. Asano, S. Tsukuda, M. Sugimoto, A. Kishimura, K. Kataoka, and S. Seki, Sci. Rep., 2 (2012) 600.
28. G. M. Wallraff and W. D. Hinsberg, Chem. Rev., 99 (1999) 1801.
29. M. Omichi, H. Marui, V. S. Padalkar, A. Horio, S. Tsukuda, M. Sugimoto, and S. Seki, Langmuir, 31 (2015) 11692.
30. S. Tsukuda, S. Seki, M. Sugimoto, and S. Tagawa, J. Phys. Chem. B, 110 (2006) 19319.
31. Y. Liang, C. Zhen, D. Zou, and D. Xu, J. Am. Chem. Soc., 126 (2004) 16338.
32. T. Sakurai, S. Sakaguchi, Y. Takeshita, K. Kayama, A. Horio, M. Sugimoto, T. Yamaki, A. Chiba, Y. Saitoh, L. B. V. S. Garimella, D. K. Avasthi, and S. Seki, ACS Appl. Nano Mater., 3 (2020) 6043.
33. H. G. Paretzke, “Kinetics of Nonhomogeneous Processes”, G. R. Freeman, Ed., Wiley, New York, 1987, Ch. 3, pp. 89–170.
34. S. Kazaoui, R. Ross, and N. Minami, Solid State Commun., 90 (1994) 623.
35. A. A. M. Farag, Opt. Laser. Technol., 39 (2007) 728.
36. R. L. McCreery, “Raman Spectroscopy for Chemical Analysis” J. D. Winefordner, Ed., Wiley, New York 2000, Ch. 1, pp. 1–14.
37. M. S. Dresselhaus, G. Dresselhaus, and P. C. Eklund, J. Raman Spectrosc., 27 (1996) 351.
38. A. J. Bovill, A. A. McConnel, J. A. Nimmo, and W. E. Smith, J. Phys. Chem., 90 (1986) 569.
39. A. Asano, M. Omichi, S. Tsukuda, K. Takano, M. Sugimoto, A. Saeki, and S. Seki, J. Phys. Chem. C, 116 (2012) 17274.