SWCNTs in Nanoelectronics

Subjects: Physics, Applied
Contributor: Marianna V. Kharlamova

The unique tailored electronic properties of single-walled carbon nanotubes (SWCNTs) render them promising platforms for nanoelectronics applications.

Keywords: single-walled carbon nanotube ; nanoelectronics ; FET

1. Introduction

The Encyclopedia entry "SWCNTs in Nanoelectronics" is dedicated to applications of filled single-walled carbon nanotubes (SWCNTs).

Their unique tailored electronic properties render them promising platforms for nanoelectronics applications. Molecules, simple substances and chemical compounds can be filled inside SWCNTs. Encapsulated molecules can lead to *p*- or *n*-doping of SWCNTs. Organic molecules, organometallic molecules result in *n*- [1][2][3][4][5][6][7][8][9][10][11][12][13][14][15][16] or *p*-doping of nanotubes [1][2][17][18][19][20][21][22][23][24][25][26].

In work [27], authors built and tested field effect transistors (FETs) with C_{60} filled SWCNT (C_{60}-peapods) as active channels. Electrical resistivity, thermal conductivity and thermopower of unfilled SWCNTs and C_{60}-peapods were measured in Ref. [28]. Also, other authors measured the transport properties of C_{60}-peapods [29][30][31][32][33] and theoretical calculations were conducted [24].

The properties of fullerene-filled SWCNTs and SWCNTs filled with endohedral fullerenes were compared that allowed to directly investigate the effects of an altered filler on the hosting SWCNTs [34][35][36][37][38][39][40][41]. In Ref. [41], a temperature-dependent transition between *p*- and *n*-type conductivity was observed. The transport properties of C_{60} fullerene peapods and gadolinium metallofullerene ($Gd@C_{82}$) peapods implemented in FETs as channels were explored. The fullerene-filled SWCNTs exhibited *p*-type electronic characteristics, which was also observed for semiconducting SWCNTs [42][43]. $Gd@C_{82}$-filled SWCNTs had ambipolar *p*- and *n*-type electronic behavior.

Piecewise filling can create *p*-*n* junctions along SWCNTs. Demonstrated examples are partially Fe-filled SWCNTs [44] and the piecewise co-filling of SWCNTs with Cs and I or C_{60} [45]. Figures 1a and b depict contour plots of I_{DS} as functions of V_{DS} and V_G for Cs/I@SWCNTs and Cs/C_{60}@SWCNTs recorded at room temperature, respectively [45]. Calculations of the chemical potential along the tube axis were carried out. In order to account for the different *p*-*n* junction occurring in Cs/I@SWCNTs and Cs/C_{60}@SWCNTs. Figure 1c is the calculated potential profile across the *p*-*n* junction. If the doping densities are equal (donor density: N_D = acceptor density: N_A) in the *n* and *p* regions, the potential at the depletion layer is symmetric and the depletion lengths (l_p and l_n) are symmetric (top of Fig. 1c). If the donor density dominates like $N_D = 10N_A$ (the bottom of Fig. 1c) the depletion layer in the p region becomes much wider than in the *n* region (l_n) and the potential across the junction is very asymmetric [45].

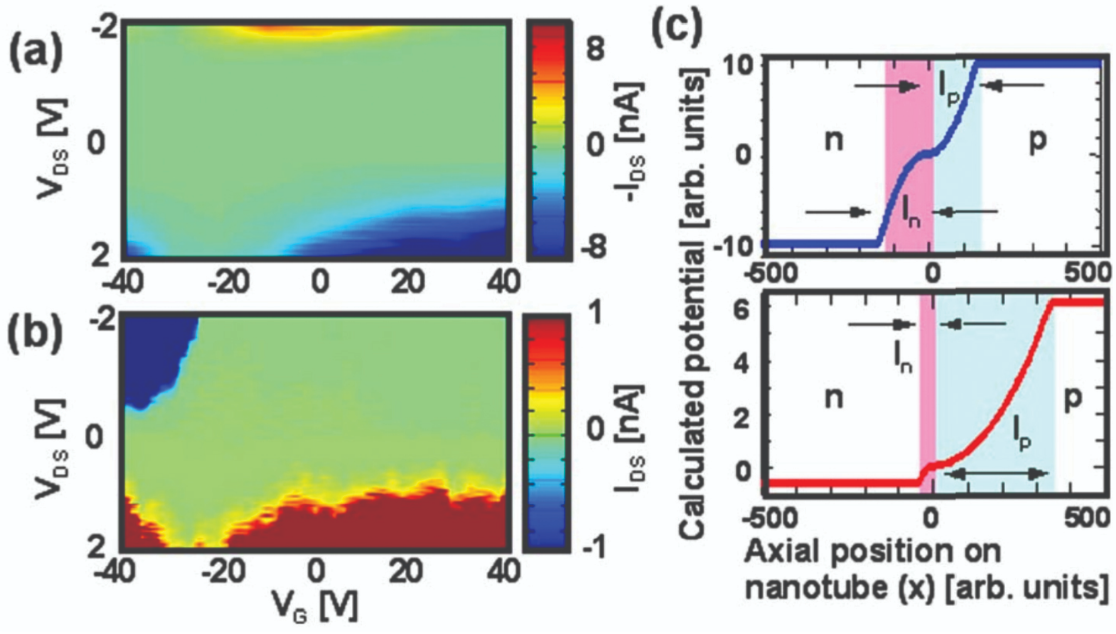

Figure 1. Contour plots of I_{DS} as functions of V_G and V_{DS} for (a) Cs/I@SWCNTs and (b) Cs/C_{60}@SWCNTs measured at room temperature. (c) Calculated potential profiles with depletion regions around the *p-n* junction area. $N_D = N_A$ (top) and $N_D = 10N_A$ (bottom). Reprinted from [45] with the permission of AIP Publishing.

Encapsulated metals [46][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61][62][63] lead to n-doping of SWCNTs. The transport properties of FETs with channels made of ferrocene-filled SWCNTs and Fe-filled SWCNTs were directly compared [64]. This comparison revealed that, while Fe-filled SWCNTs exhibited high performance unipolar *n*-type characteristics, ferrocene-filled SWCNTs are indeed ambipolar semiconductors.

2. Future

The hitherto developments of carbon nanotube-based nanoelectronics have proven fundamental building blocks and prepared the ground for exploring novel types of filled SWCNTs as specialized building blocks. Foreseeable next step would be the realization of devices based on SWCNTs filled with various non-metals [65], metal oxides [46], metal halogenides [66][67][68][69][70][71][72][73][74][75][76][77][78][47][79][80][81][82][83][84][85][86][87][88][89][90] and metal chalcogenides [47][91][92]. With all the available experience on filling of SWCNTs with a wide range of substances many novel transport characteristics are yet to be explored as building blocks for carbon nanotube-electronics.

References

1. Takenobu, T.; Takano, T.; Shiraishi, M.; Murakami, Y.; Ata, M.; Kataura, H.; Achiba, Y.; Iwasa, Y. Stable and controlled amphoteric doping by encapsulation of organic molecules inside carbon nanotubes. Nat. Mater. 2003, 2, 683–688.
2. Lu, J.; Nagase, S.; Yu, D.P.; Ye, H.Q.; Han, R.S.; Gao, Z.X.; Zhang, S.; Peng, L.M. Amphoteric and controllable doping of carbon nanotubes by encapsulation of organic and organometallic molecules. Phys.Rev.Lett. 2004, 93, 116804.
3. Li, L.J.; Khlobystov, A.N.; Wiltshire, J.G.; Briggs, G.A.D.; Nicholas, R.J. Diameter-selective encapsulation of metallocenes in single-walled carbon nanotubes. Nat. Mater. 2005, 4, 481–485.
4. Garcia-Suarez, V.M.; Ferrer, J.; Lambert, C.J. Tuning the electrical conductivity of nanotube-encapsulated metallocene wires. Phys. Rev. Lett. 2006, 96, 106804.
5. Sceats, E.L.; Green, J.C. Noncovalent interactions between organometallic metallocene complexes and single-walled carbon nanotubes. J. Chem. Phys. 2006, 125, 154704.
6. Shiozawa, H.; Pichler, T.; Gruneis, A.; Pfeiffer, R.; Kuzmany, H.; Liu, Z.; Suenaga, K.; Kataura, H. A catalytic reaction inside a single-walled carbon nanotube. Adv. Mater. 2008, 20, 1443–1449.
7. Shiozawa, H.; Pichler, T.; Kramberger, C.; Gruneis, A.; Knupfer, M.; Buchner, B.; Zolyomi, V.; Koltai, J.; Kurti, J.; Batchelor, D.; et al. Fine tuning the charge transfer in carbon nanotubes via the interconversion of encapsulated molecules. Phys. Rev. B 2008, 77, 153402.
8. Sauer, M.; Shiozawa, H.; Ayala, P.; Ruiz-Soria, G.; Kataura, H.; Yanagi, K.; Krause, S.; Pichler, T. In situ filling of metallic single-walled carbon nanotubes with ferrocene molecules. Phys. Status Solidi B-Basic Solid State Phys. 2012,

249, 2408–2411.

9. Liu, X.J.; Kuzmany, H.; Ayala, P.; Calvaresi, M.; Zerbetto, F.; Pichler, T. Selective Enhancement of Photoluminescence in Filled Single-Walled Carbon Nanotubes. Adv. Funct. Mater. 2012, 22, 3202–3208.
10. Kharlamova, M.V.; Sauer, M.; Saito, T.; Krause, S.; Liu, X.; Yanagi, K.; Pichler, T.; Shiozawa, H. Inner tube growth properties andelectronic structure offerrocene-filled large diametersingle-walled carbon nanotubes. Phys. Status Solidi B-Basic Solid State Phys. 2013, 250, 2575–2580.
11. Sauer, M.; Shiozawa, H.; Ayala, P.; Ruiz-Soria, G.; Liu, X.J.; Chernov, A.; Krause, S.; Yanagi, K.; Kataura, H.; Pichler, T. Internal charge transfer in metallicity sorted ferrocene filled carbon nanotube hybrids. Carbon 2013, 59, 237–245.
12. Kharlamova, M.V.; Sauer, M.; Saito, T.; Sato, Y.; Suenaga, K.; Pichler, T.; Shiozawa, H. Doping of single-walled carbon nanotubes controlled via chemical transformation of encapsulated nickelocene. Nanoscale 2015, 7, 1383–1391.
13. Kharlamova, M.V.; Sauer, M.; Egorov, A.; Kramberger, C.; Saito, T.; Pichler, T.; Shiozawa, H. Temperature-dependent inner tube growth and electronic structure of nickelocene-filled single-walled carbon nanotubes. Phys. Status Solidi B-Basic Solid State Phys. 2015, 252, 2485–2490.
14. Kharlamova, M.V.; Kramberger, C.; Sauer, M.; Yanagi, K.; Saito, T.; Pichler, T. Inner tube growth and electronic properties of metallicity-sorted nickelocene-filled semiconducting single-walled carbon nanotubes. Appl. Phys. A 2018, 1124, 247.
15. Shiozawa, H.; Pichler, T.; Kramberger, C.; Rummeli, M.; Batchelor, D.; Liu, Z.; Suenaga, K.; Kataura, H.; Silva, S.R.P. Screening the Missing Electron: Nanochemistry in Action. Phys. Rev. Lett. 2009, 102, 046804.
16. Shiozawa, H.; Kramberger, C.; Rummeli, M.; Batchelor, D.; Kataura, H.; Pichler, T.; Silva, S.R.P. Electronic properties of single-walled carbon nanotubes encapsulating a cerium organometallic compound. Phys. Status Solidi B-Basic Solid StatePhys. 2009, 246, 2626–2630.
17. Liu, X.; Pichler, T.; Knupfer, M.; Golden, M.S.; Fink, J.; Kataura, H.; Achiba, Y.; Hirahara, K.; Iijima, S. Filling factors, structural, and electronic properties of C-60 molecules in single-wall carbon nanotubes. Phys.Rev.B 2002, 65, 045419.
18. Shiozawa, H.; Ishii, H.; Kihara, H.; Sasaki, N.; Nakamura, S.; Yoshida, T.; Takayama, Y.; Miyahara, T.; Suzuki, S.; Achiba, Y.; et al. Photoemission and inverse photoemission study of the electronic structure of C-60 fullerenes encapsulated in single-walled carbon nanotubes. Phys. Rev. B 2006, 73, 075406.
19. Du, M.H.; Cheng, H.P. Manipulation of fullerene-induced impurity states in carbon peapods. Phys. Rev. B 2003, 68, 113402.
20. Dubay, O.; Kresse, G. Density functional calculations for C 60 peapods. Phys. Rev. B 2004, 70, 165424.
21. Lu, J.; Nagase, S.; Zhang, S.; Peng, L.M. Strongly size-dependent electronic properties in C-60-encapsulated zigzag nanotubes and lower size limit of carbon nanopeapods. Phys. Rev. B 2003, 68, 121402.
22. Okada, S.; Otani, M.; Oshiyama, A. Electron-state control of carbon nanotubes by space and encapsulated fullerenes. Phys. Rev. B 2003, 67, 205411.
23. Otani, M.; Okada, S.; Oshiyama, A. Energetics and electronic structures of one-dimensional fullerene chains encapsulated in zigzag nanotubes. Phys. Rev. B 2003, 68, 125424.
24. Rochefort, A. Electronic and transport properties of carbon nanotube peapods. Phys. Rev. B 2003, 67, 115401.
25. Pichler, T.; Kramberger, C.; Ayala, P.; Shiozawa, H.; Knupfer, M.; Rummeli, M.H.; Batchelor, D.; Kitaura, R.; Imazu, N.; Kobayashi, K.; et al. Bonding environment and electronic structure of Gd metallofullerene and Gd nanowire filled single-wall carbon nanotubes. Phys. Status Solidi B-Basic Solid StatePhys. 2008, 245, 2038–2041.
26. Ayala, P.; Kitaura, R.; Kramberger, C.; Shiozawa, H.; Imazu, N.; Kobayashi, K.; Mowbray, D.J.; Hoffmann, P.; Shinohara, H.; Pichler, T. A Resonant Photoemission Insight to the Electronic Structure of Gd Nanowires Templated in the Hollow Core of SWCNTs. Mater. Express 2011, 1, 30–35.
27. Yu, H.Y.; Lee, D.S.; Lee, S.H.; Kim, S.S.; Lee, S.W.; Park, Y.W.; Dettlaff-Weglikowskaand, U.; Roth, S. Single-electron transistor mediated by C-60 insertion inside a carbon nanotube. Appl. Phys. Lett. 2005, 87, 163118.
28. Vavro, J.; Llaguno, M.C.; Satishkumar, B.C.; Luzzi, D.E.; Fischer, J.E. Electrical and thermal properties of C-60-filled single-wall carbon nanotubes. Appl. Phys. Lett. 2002, 80, 1450–1452.
29. Hongo, H.; Nihey, F.; Yudasaka, M.; Ichihashi, T.; Iijima, S. Transport properties of single-wall carbon nanotubes with encapsulated C-60. Phys. B 2002, 323, 244–245.
30. Hirahara, K.; Suenaga, K.; Bandow, S.; Kato, H.; Okazaki, T.; Shinohara, H.; Iijima, S. One-dimensional metallofullerene crystal generated inside single-walled carbon nanotubes. Phys. Rev. Lett. 2000, 85, 5384–5387.

31. Utko, P.; Nygard, J.; Monthioux, M.; Noe, L. Sub-Kelvin transport spectroscopy of fullerene peapod quantum dots. Appl. Phys. Lett. 2006, 89, 233118.

32. Eliasen, A.; Paaske, J.; Flensberg, K.; Smerat, S.; Leijnse, M.; Wegewijs, M.R.; Jorgensen, H.I.; Monthioux, M.; Nygard, J. Transport via coupled states in a C-60 peapod quantum dot. Phys. Rev. B 2010, 81, 155431.

33. Kharlamova, M.V. Nickelocene-Filled Purely Metallic Single-Walled CarbonNanotubes: Sorting and Tuning the Electronic Properties. Nanomaterials 2021, 11(10), 2500.

34. Lee, J.; Kim, H.; Kahng, S.J.; Kim, G.; Son, Y.W.; Ihm, J.; Kato, H.; Wang, Z.W.; Okazaki, T.; Shinohara, H.; et al. Bandgap modulation of carbon nanotubes by encapsulated metallofullerenes. Nature 2002, 415, 1005–1008.

35. Okazaki, T.; Shimada, T.; Suenaga, K.; Ohno, Y.; Mizutani, T.; Lee, J.; Kuk, Y.; Shinohara, H. Electronic properties of metallofullerene peapods: (Gd @ C-82)(n)@SWNTs. Appl. Phys. A 2003, 76, 475–478.

36. Shimada, T.; Okazaki, T.; Taniguchi, R.; Sugai, T.; Shinohara, H.; Suenaga, K.; Ohno, Y.; Mizuno, S.; Kishimoto, S.; Mizutani, T. Ambipolar field-effect transistor behavior of metallofullerene peapods. Appl. Phys. Lett. 2002, 81, 4067–4069.

37. Kharlamova, M.V.; Kramberger, C.; Yanagi, K.; Sauer, M.; Saito, T.; Pichler, T. Separation of Nickelocene-Filled Single-Walled CarbonNanotubes by Conductivity Type and Diameter. Phys. Status Solidi B 2017, 254(11), 1700178.

38. Shimada, T.; Ohno, Y.; Okazaki, T.; Sugai, T.; Suenaga, K.; Kishimoto, S.; Mizutani, T.; Inoue, T.; Taniguchi, R.; Fukui, N.; et al. Transport properties of C-78, C-90 and fullerenes-nanopeapods by field effect transistors. Phys. E 2004, 21, 1089–1092.

39. Kharlamova, M.V.; Kramberger, C.; Rudatis, P.; Pichler, T.; Eder, D. Revealing the doping effect of encapsulated lead halogenides on single-walled carbon nanotubes. Appl. Phys. A 2019, 125, 320.

40. Chiu, P.W.; Gu, G.; Kim, G.T.; Philipp, G.; Roth, S.; Yang, S.F.; Yang, S. Temperature-induced change from p to n conduction in metallofullerene nanotube peapods. Appl. Phys. Lett. 2001, 79, 3845–3847.

41. Chiu, P.W.; Yang, S.F.; Yang, S.H.; Gu, G.; Roth, S. Temperature dependence of conductance character in nanotube peapods. Appl. Phys. A 2003, 76, 463–467.

42. Shea, H.R.; Martel, R.; Hertel, T.; Schmidt, T.; Avouris, P. Manipulation of carbon nanotubes and properties of nanotube field-effect transistors and rings. Microelectron. Eng. 1999, 46, 101–104.

43. Kharlamova, M.V.; Kramberger, C.; Rudatis, P.; Yanagi, K.; Eder, D. Characterization of the Electronic Properties ofSingle-Walled Carbon Nanotubes Filled with an ElectronDonor-Rubidium Iodide: Multifrequency Raman and X-rayPhotoelectron Spectroscopy Studies. Phys. Status Solidi B 2019, 256, 1900209.

44. Li, Y.; Hatakeyama, R.; Shishido, J.; Kato, T.; Kaneko, T. Air-stable p-n junction diodes based on single-walled carbon nanotubes encapsulating Fe nanoparticles. Appl. Phys. Lett. 2007, 90, 173127.

45. Kato, T.; Hatakeyama, R.; Shishido, J.; Oohara, W.; Tohji, K. P-N junction with donor and acceptor encapsulated single-walled carbon nanotubes. Appl. Phys. Lett. 2009, 95, 083109.

46. Corio, P.; Santos, A.P.; Santos, P.S.; Temperini, M.L.A.; Brar, V.W.; Pimenta, M.A.; Dresselhaus, M.S. Characterization of single wall carbon nanotubes filled with silver and with chromium compounds. Chem. Phys. Lett. 2004, 383, 475–480.

47. Kharlamova, M.V.; Yashina, L.V.; Lukashin, A.V. Comparison of modification of electronic properties of single-walled carbon nanotubes filled with metal halogenide, chalcogenide, and pure metal. Appl. Phys. A 2013, 112, 297–304.

48. Kharlamova, M.V.; Niu, J.J. Comparison of metallic silver and copper doping effects on single-walled carbon nanotubes. Appl. Phys. A 2012, 109, 25–29.

49. Kharlamova, M.V.; Niu, J.J. Donor doping of single-walled carbon nanotubes by filling of channels with silver. J. Exp. Theor. Phys. 2012, 115, 485–491.

50. Borowiak-Palen, E.; Ruemmeli, M.H.; Gemming, T.; Pichler, T.; Kalenczuk, R.J.; Silva, S.R.P. Silver filled single-wall carbon nanotubes-synthesis, structural and electronic properties. Nanotechnology 2006, 17, 2415–2419.

51. Fagan, S.B.; Filho, A.G.S.; Filho, J.M.; Corio, P.; Dresselhaus, M.S. Electronic properties of Ag- and CrO3-filled single-wall carbon nanotubes. Chem. Phys. Lett. 2005, 406, 54–59.

52. Li, W.F.; Zhao, M.W.; Xia, Y.Y.; He, T.; Song, C.; Lin, X.H.; Liu, X.D.; Mei, L.M. Silver-filled single-walled carbon nanotubes: Atomic and electronic structures from first-principles calculations. Phys. Rev. B 2006, 74, 195421.

53. Kharlamova, M.V.; Niu, J.J. New method of the directional modification of the electronic structure of single-walled carbon nanotubes by filling channels with metallic copper from a liquid phase. JETP Lett. 2012, 95, 314–319.

54. Nakanishi, R.; Kitaura, R.; Ayala, P.; Shiozawa, H.; De Blauwe, K.; Hoffmann, P.; Choi, D.; Miyata, Y.; Pichler, T.; Shinohara, H. Electronic structure of Eu atomic wires encapsulated inside single-wall carbon nanotubes. Phys. Rev. B 2012, 86, 115445.

55. Zhou, J.; Yan, X.; Luo, G.F.; Qin, R.; Li, H.; Lu, J.; Mei, W.N.; Gao, Z.X. Structural, Electronic, and Transport Properties of Gd/Eu Atomic Chains Encapsulated in Single-Walled Carbon Nanotubes. J. Phys. Chem. C 2010, 114, 15347–15353.

56. Galpern, E.G.; Stankevich, I.V.; Chistykov, A.L.; Chernozatonskii, L.A. Carbon Nanotubes with Metal Inside-Electron-Structure of Tubelenes N and N. Chem. Phys. Lett. 1993, 214, 345–348.

57. Du, X.J.; Zhang, J.M.; Wang, S.F.; Xu, K.W.; Ji, V. First-principle study on energetics and electronic structure of a single copper atomic chain bound in carbon nanotube. Eur. Phys. J. B 2009, 72, 119–126.

58. Ivanovskaya, V.V.; Kohler, C.; Seifert, G. 3d metal nanowires and clusters inside carbon nanotubes: Structural, electronic, and magnetic properties. Phys. Rev. B 2007, 75, 075410.

59. Kang, Y.J.; Choi, J.; Moon, C.Y.; Chang, K.J. Electronic and magnetic properties of single-wall carbon nanotubes filled with iron atoms. Phys. Rev. B 2005, 71, 115441.

60. Meunier, V.; Muramatsu, H.; Hayashi, T.; Kim, Y.A.; Shimamoto, D.; Terrones, H.; Dresselhaus, M.S.; Terrones, M.; Endo, M.; Sumpter, B.G. Properties of One-Dimensional Molybdenum Nanowires in a Confined Environment. Nano Lett. 2009, 9, 1487–1492.

61. Parq, J.H.; Yu, J.; Kim, G. First-principles study of ultrathin (2 × 2) Gd nanowires encapsulated in carbon nanotubes. J. Chem. Phys. 2010, 132, 054701.

62. Sun, Y.; Yang, X.B.; Ni, J. Bonding differences between single iron atoms versus iron chains with carbon nanotubes: First-principles calculations. Phys. Rev. B 2007, 76, 035407.

63. Xie, Y.; Zhang, J.M.; Huo, Y.P. Structural, electronic and magnetic properties of hcp Fe, Co and Ni nanowires encapsulated in zigzag carbon nanotubes. Eur. Phys. J. B 2011, 81, 459–465.

64. Li, Y.F.; Hatakeyama, R.; Kaneko, T.; Izumida, T.; Okada, T.; Kato, T. Electrical properties of ferromagnetic semiconducting single-walled carbon nanotubes. Appl. Phys. Lett. 2006, 89, 083117.

65. Chernysheva, M.V.; Kiseleva, E.A.; Verbitskii, N.I.; Eliseev, A.A.; Lukashin, A.V.; Tretyakov, Y.D.; Savilov, S.V.; Kiselev, N.A.; Zhigalina, O.M.; Kumskov, A.S.; et al. The electronic properties of SWNTs intercalated by electron acceptors. Phys. E 2008, 40, 2283–2288.

66. Zakalyukin, R.M.; Mavrin, B.N.; Dem'yanets, L.N.; Kiselev, N.A. Synthesis and characterization of single-walled carbon nanotubes filled with the superionic material SnF2. Carbon 2008, 46, 1574–1578.

67. Kharlamova, M.V.; Kramberger, C.; Mittelberger, A.; Yanagi, K.; Pichler, T.; Eder, D. Silver Chloride Encapsulation-Induced Modifications of Raman Modes of Metallicity-Sorted Semiconducting Single-Walled Carbon Nanotubes. J. Spectrosc. 2018, 2018, 5987428.

68. Kharlamova, M.V.; Kramberger, C.; Domanov, O.; Mittelberger, A.; Yanagi, K.; Pichler, T.; Eder, D. Fermi level engineering of metallicity-sorted metallic single-walled carbon nanotubes by encapsulation of few-atom-thick crystals of silver chloride. J. Mater. Sci. 2018, 53, 13018–13029.

69. Kharlamova, M.V.; Kramberger, C.; Domanov, O.; Mittelberger, A.; Saito, T.; Yanagi, K.; Pichler, T.; Eder, D. Comparison of Doping Levels of Single-Walled Carbon Nanotubes Synthesized by Arc-Discharge and Chemical Vapor Deposition Methods by Encapsulated Silver Chloride. Phys. Status Solidi B-Basic Solid State Phys. 2018, 255, 1800178.

70. Eliseev, A.A.; Yashina, L.V.; Brzhezinskaya, M.M.; Chernysheva, M.V.; Kharlamova, M.V.; Verbitsky, N.I.; Lukashin, A.V.; Kiselev, N.A.; Kumskov, A.S.; Zakalyuhin, R.M.; et al. Structure and electronic properties of AgX (X = Cl, Br, I)-intercalated single-walled carbon nanotubes. Carbon 2010, 48, 2708–2721.

71. Kharlamova, M.V.; Brzhezinskaya, M.; Vinogradov, A.; Suzdalev, I.; Maksimov, Y.V.; Imshennik, V.; Novichikhin, S.V.; Krestinin, A.V.; Yashina, L.V.; Lukashin, A.V.; et al. The forming and properties of one-dimensional FeHal 2 (Hal=Cl, Br, I) nanocrystals in channels of single-walled carbon nanotubes. Russ. Nanotechnologies. 2009, 4, 77–8787.

72. Kharlamova, M.V.; Eliseev, A.A.; Yashina, L.V.; Petukhov, D.I.; Liu, C.P.; Wang, C.Y.; Semenenko, D.A.; Belogorokhov, A.I. Study of the electronic structure of single-walled carbon nanotubes filled with cobalt bromide. JETP Lett. 2010, 91, 196–200.

73. Kharlamova, M.V.; Yashina, L.V.; Eliseev, A.A.; Volykhov, A.A.; Neudachina, V.S.; Brzhezinskaya, M.M.; Zyubina, T.S.; Lukashin, A.V.; Tretyakov, Y.D. Single-walled carbon nanotubes filled with nickel halogenides: Atomic structure and doping effect. Phys. Status Solidi B-Basic Solid State Phys. 2012, 249, 2328–2332.

74. Kharlamova, M.V. Raman Spectroscopy Study of the Doping Effect of the Encapsulated Iron, Cobalt, and Nickel Bromides on Single-Walled Carbon Nanotubes. J. Spectrosc. 2015, 2015, 653848.
75. Kharlamova, M.V.; Eliseev, A.A.; Yashina, L.V.; Lukashin, A.V.; Tretyakov, Y.D. Synthesis of Nanocomposites on Basis of Single-walled Carbon Nanotubes Intercalated by Manganese Halogenides. J. Phys. Conf. Ser. 2012, 345, 012034.
76. Kharlamova, M.V. Electronic properties of single-walled carbon nanotubes filled with manganese halogenides. Appl. Phys. A 2016, 122, 791.
77. Kharlamova, M.V.; Yashina, L.V.; Volykhov, A.A.; Niu, J.J.; Neudachina, V.S.; Brzhezinskaya, M.M.; Zyubina, T.S.; Belogorokhov, A.I.; Eliseev, A.A. Acceptor doping of single-walled carbon nanotubes by encapsulation of zinc halogenides. Eur. Phys. J. B. 2012, 85, 34.
78. Kharlamova, M.V. Comparison of influence of incorporated 3d-, 4d-and 4f-metal chlorides on electronic properties of single-walled carbon nanotubes. Appl. Phys. A 2013, 111, 725–731.
79. Ayala, P.; Kitaura, R.; Nakanishi, R.; Shiozawa, H.; Ogawa, D.; Hoffmann, P.; Shinohara, H.; Pichler, T. Templating rare-earth hybridization via ultrahigh vacuum annealing of ErCl3 nanowires inside carbon nanotubes. Phys. Rev. B 2011, 83, 085407.
80. Kharlamova, M.V.; Volykhov, A.A.; Yashina, L.V.; Egorov, A.V.; Lukashin, A.V. Experimental and theoretical studies on the electronic properties of praseodymium chloride-filled single-walled carbon nanotubes. J. Mater. Sci 2015, 50, 5419–5430.
81. Kharlamova, M.V. Rare-earth metal halogenide encapsulation-induced modifications in Raman spectra of single-walled carbon nanotubes. Appl. Phys. A 2015, 118, 27–35.
82. Eliseev, A.A.; Yashina, L.V.; Verbitskiy, N.I.; Brzhezinskaya, M.M.; Kharlamova, M.V.; Chernysheva, M.V.; Lukashin, A.V.; Kiselev, N.A.; Kumskov, A.S.; Freitag, B.; et al. Interaction between single walled carbon nanotube and 1D crystal in (X = Cl, Br, I) nanostructures. Carbon 2012, 50, 4021–4039.
83. Chernysheva, M.V.; Eliseev, A.A.; Lukashin, A.V.; Tretyakov, Y.D.; Savilov, S.V.; Kiselev, N.A.; Zhigalina, O.M.; Kumskov, A.S.; Krestinin, A.V.; Hutchison, J.L. Filling of single-walled carbon nanotubes by CuI nanocrystals via capillary technique. Phys. E 2007, 37, 62–65.
84. Kumskov, A.S.; Zhigalina, V.G.; Chuvilin, A.L.; Verbitskiy, N.I.; Ryabenko, A.G.; Zaytsev, D.D.; Eliseev, A.A.; Kiselev, N.A. The structure of 1D and 3D CuI nanocrystals grown within 1.5–2.5 nm single wall carbon nanotubes obtained by catalyzed chemical vapor deposition. Carbon 2012, 50, 4696–4704.
85. Fedotov, P.V.; Tonkikh, A.A.; Obraztsova, E.A.; Nasibulin, A.G.; Kauppinen, E.I.; Chuvilin, A.L.; Obraztsova, E.D. Optical properties of single-walled carbon nanotubes filled with CuCl by gas-phase technique. Phys. Status Solidi B-Basic Solid State Phys. 2014, 251, 2466–2470.
86. Kharlamova, M.V.; Yashina, L.V.; Lukashin, A.V. Charge transfer in single-walled carbon nanotubes filled with cadmium halogenides. J. Mater. Sci. 2013, 48, 8412–8419.
87. Kharlamova, M.V.; Kramberger, C.; Mittelberger, A. Raman spectroscopy study of the doping effect of the encapsulated terbium halogenides on single-walled carbon nanotubes. Appl. Phys. A 2017, 123, 239.
88. Sceats, E.L.; Green, J.C.; Reich, S. Theoretical study of the molecular and electronic structure of one-dimensional crystals of potassium iodide and composites formed upon intercalation in single-walled carbon nanotubes. Phys. Rev. B 2006, 73, 125441.
89. Yam, C.Y.; Ma, C.C.; Wang, X.J.; Chen, G.H. Electronic structure and charge distribution of potassium iodide intercalated single-walled carbon nanotubes. Appl. Phys. Lett. 2004, 85, 4484–4486.
90. Christ, K.V.; Sadeghpour, H.R. Energy dispersion in graphene and carbon nanotubes and molecular encapsulation in nanotubes. Phys. Rev. B 2007, 75, 195418.
91. Kharlamova, M.V. Novel approach to tailoring the electronic properties of single-walled carbon nanotubes by the encapsulation of high-melting gallium selenide using a single-step process. JETP Lett. 2013, 98, 272–277.
92. Kharlamova, M.V. Comparative analysis of electronic properties of tin, gallium, and bismuth chalcogenide-filled single-walled carbon nanotubes. J. Mater. Sci. 2014, 49, 8402–8411.