SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Experimental Investigation of Magnetic Properties of β-SiC Nanoparticle at Room Temperature

Najib Mohammed Sultan[1,*], Thar M. Badri Albarody[1], Masri Baharom[1], Husam Kareem Mohsin Al-Jothery[1,2], Haetham G. Mohammed[1]

[1] Department of Mechanical Engineering, Universiti Teknologi PETRONAS (UTP), 32610 Bandar Seri Iskandar, Perak, Malaysia
[2] Mechanical Engineering Department, University of Al-Qadisiyah, Al-Diwaniyah 58001, Qadisiyah, Iraq

ARTICLE INFO

Article history:
Received 22 July 2023
Received in revised form 26 November 2023
Accepted 5 December 2023
Available online 15 December 2023

Keywords:
Spintronics; nanoparticle; magnetic; point defect; β-Sic; semiconductor; dilute magnetic semiconductor

ABSTRACT

In this paper, magnetic properties of β-SiC nanoparticles have been studied. Results showed intrinsic at room temperature. The applied magnetic field observes a magnetization value of 50.972E-3 emu/g with remnant magnetization is 3E-3 emu/g. The measured value of coercivity found to be 89.068 G at squareness ratio is 0.043524. The room temperature ferromagnetic in β-SiC possibly originated from dangling effect vacancy of silicon and carbon with the nearest neighbour carbon atom have strong s-p hybridization. The result of this paper might indicate a promising pathway of developing a novel spintronics based β-SiC nanoparticle.

1. Introduction

Nowadays, silicon carbide is under investigation as an enabling material for a variety of new semiconductor devices in spintronics [1,2]. SiC is widely utilized in various applications, including high-voltage, high-temperature, and high-power microwave applications within the 1-10 GHz frequency range, as well as high-power electronic applications. Additionally, SiC can be doped with semiconductor materials, such as germanium, to enhance its lattice crystal structure and improve its electrical properties [3]. Silicon dioxide (SiO_2) has low life a temperature above 300° [4] which is drawback of dielectric that used as gate metal in metal–oxide–semiconductor field-effect transistor of compared to silicon carbide which has long life a temperature above 2700° which preferred to use silicon carbide as the dielectric layer for these types of application. Silicon carbide (SiC) exists in various phases, each having different lattice structures known as polytypes. The notable polytypes include β-SiC, 4H-SiC, and 6H-SiC, with distinct band energy gap values of 2.2-2.4 eV, 3.23 eV, and 3 eV, respectively. Silicon carbide exhibits high oxidation resistance, high thermal conductivity, high mechanical strength, low specific weight, and chemical inertness, making it an excellent catalyst for

---

[*] *Corresponding author.*
E-mail address: najib_19000948@utp.edu.my

https://doi.org/10.37934/araset.35.1.173180

material support [5]. After the discovery of ferromagnetism (FM) in SiC crystals, the investigation of the magnetic properties of SiC became paramount importance [6]. Spintronics, also known as spin electronics, is the field of research that focuses on the role of electron (and nuclear) spin in solid-state physics, as well as the development of devices that utilize spin properties rather than charge properties in solid-state systems [7]. Wide of band gap of II-VI semiconductors have attracted a lot of attention of the researcher to produce a system like dilute magnetic semiconductor (DMS) for application in the field optoelectronics, spintronics and magnetoelectronic [8,9]. Many defective carbon-based materials, such as highly oriented pyrolytic graphite (HOPG) [10], graphene [11], oxides, and SiC [12], which are wide band gap II-VI semiconductors, have been found to exhibit sudden ferromagnetism, both experimentally and theoretically. These materials have great potential for use in the fields of organic and quantum electronics as well as in semiconductor spintronics, as a substitution for other materials. Previously, as the explained that the origin of the ferromagnetism is different from that in conventional d-electron ferromagnetic, any experiment evidence to reveal its origin will be crucial. A huge of research attempted to explain the sudden ferromagnetism in carbon based on materials [13]. Direct evidence of the origin of ferromagnetism in highly oriented pyrolytic graphite (HOPG) being localized electron states at the grain boundaries. The analysis suggests that the ferromagnetism in graphene is a result of the influence of carbon-π states and hydrogen-mediated electronic states, which have been identified as the underlying mechanism responsible for this phenomenon [14]. In graphite, the formation of local magnetic moments by single vacancies [9]. The aim of this manuscript is to investigate the natural ferromagnetism in β-SiC nanoparticles at room temperature. The room temperature ferromagnetism in β-SiC possibly originates from dangling effect vacancies of $\mathrm{V_{Si}V_C}$, where the nearest neighbor carbon atom has strong *s-p* hybridization.

2. Methodology

β-Cubic silicon carbide nanoparticles with a purity of 99.98% were purchased from Hongwu Company Berhad. The grain size and morphology of the powder was characterized utilizing a Field-Emission Scanning Electron Microscope (FE-SEM, Model Supra 55VP, Carl Zeiss AG). X-ray photoelectron spectroscopy (XPS) was used to determine the binding energy of β-SiC. Furthermore, the crystalline structure of β-Cubic silicon carbide was analysed through X-ray Powder Diffraction (XRD, Model X'Pert3 Powder, PANalytical, Cu, K-α, λ=1.540598). The magnetic measurement of the powder was measured in a vibrating-sample magnetometer (VSM). The network analyser (Keysight E5071C, ENA, specification range 8-18 GHz) was used to measure permeability.

3. Results

3.1 X-Ray Diffraction

The X-ray diffraction pattern is shown in Figure 1. The major reflection peaks of β-SiC at (111), (200), (220), (311), (222) which matched (No JCPDS Card No. 73-1665) [15]. The XRD result indicates that the sample is dominant of β-SiC having space of group of *F43m*. Scherer's formula is used to calculated crystallite size which comes around 20 nm. Lattice parameters of β-SiC nanoparticles calculated using the formula $d = a / (h2 + k2 + l2)^{1/2}$ which is well matched with theoretical and experimental value of a = 4.35962Å [16].

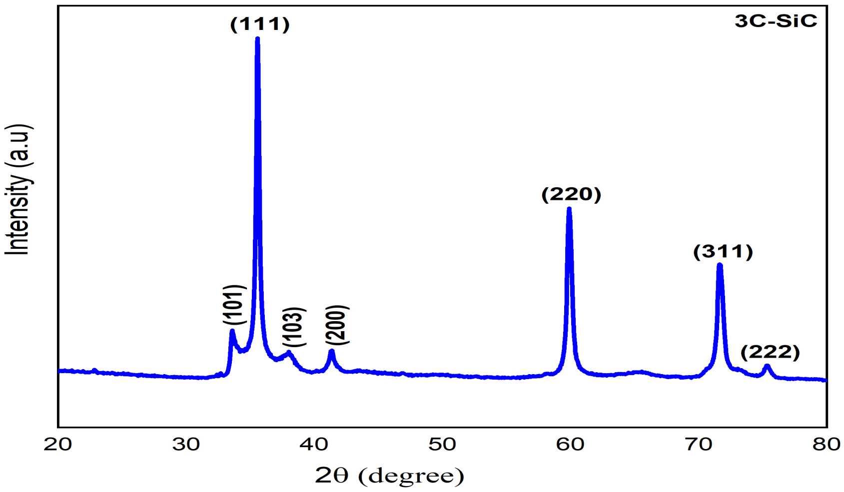
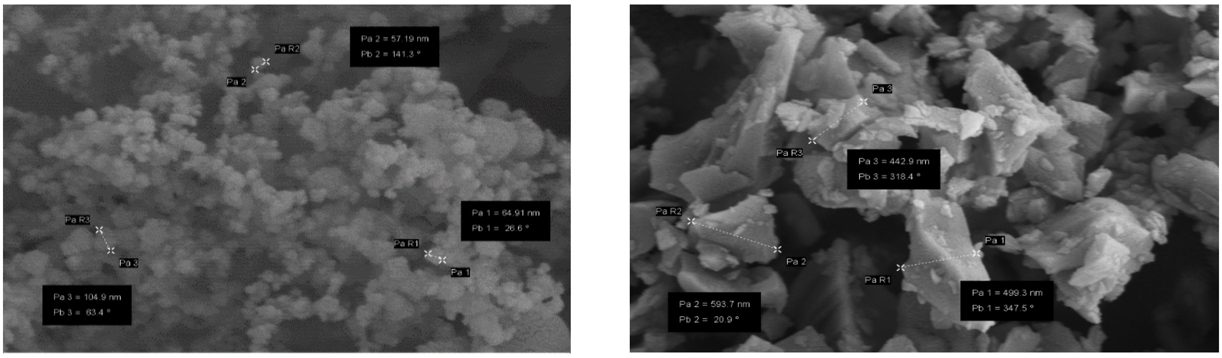


Fig. 1. X-ray diffraction for β-SiC nanoparticles

Figure 2 and Figure 3 showed the FE-SEM result of β-SiC nanoparticles. There were no other impurity phases, such as free silicon and SiO_2.



(a) (b)

Fig. 2. (a) FE-SEM of β-SiC nanoparticles; (b) FE-SEM of β-SiC nanoparticles

FE-SEM images showed the formation of micron-sized particles and the particle size varied from 60 nm to 500 nm.

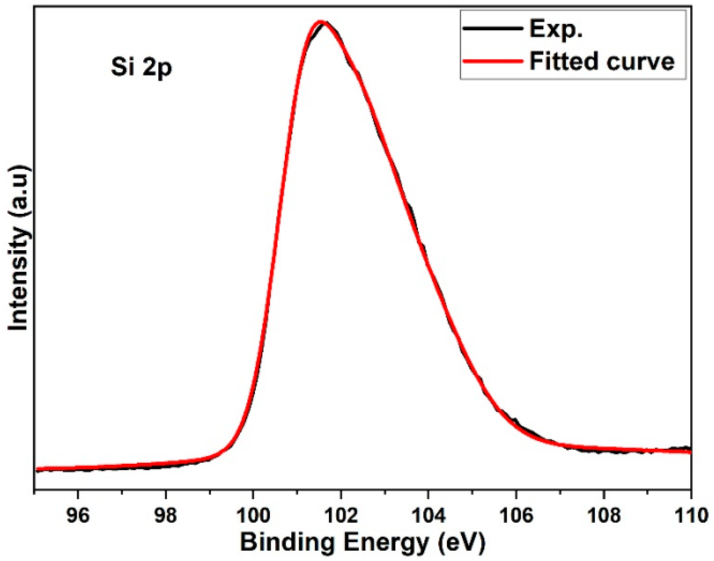


Fig. 3. Shows the X-ray photoelectron spectroscopy (XPS) spectrum of silicon p2 from the surface of crystalline β-SiC nanoparticles. The graph also includes a simulation using Gaussian distribution, represented by a dashed line, that illustrates the contribution of the Si-C bond in the β-SiC nanoparticles

Figure 3 and Figure 4 showed the result of set of the main core-level (Si 2p, C 1s) XPS spectrum of pure β-SiC nanoparticle.

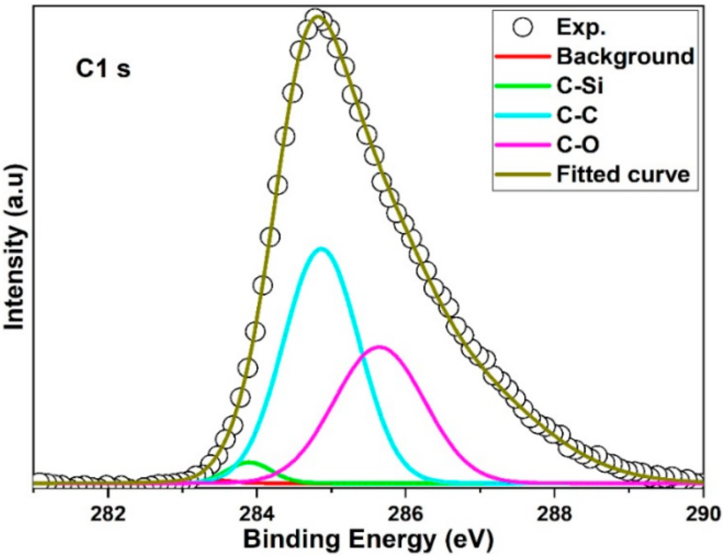


Fig. 4. XPS of C 1s spectrum

3.2 X-Ray Photoelectron Spectroscopy

The solid line in Figure 3 represents Si-p2 X-ray photoelectron spectroscopy (XPS) as a component of the spectrum. The presence of SiO_2 on the surface of β-SiC is indicated by the high binding energy and asymmetric shape of the Si p2 peaks [17]. The peak at 101.5 eV on the graph is linked to the binding energy of the Si-C bond as observed in previous records of SiC crystals [18]. The graph includes a Gaussian dashed line on the Si 2p spectrum, which indicates a clean (non-oxidized) SiC surface. The line on the graph illustrates the presence of $2p_{2/3}$- $2p_{1/2}$ the doublet components of Si bonded with C in the SiC lattice, indicating the contribution of these components to the SiC lattice as noted in [19]. As shown in Figure 4 illustrates the C 1s spectrum of β-SiC, which appears slightly asymmetric due to the presence of various coordination patterns of carbon. By using Origin software, the C 1s XPS peak can be separated into three distinct peaks. The first peak at 283.3 eV in β-SiC is related to the C-Si bond in well-crystallized SiC, as previously reported in reference [20]. The peak at 284.7 eV is caused by carbon atoms with activity in the crystal lattice forming C-C bond. The remaining peak at 285.6 eV is linked to C-O bond in adsorbed CO_2 impurities, as described in [21].

3.3 Network Analyser

The permeability ($tan\delta_m = u' - iu''$) of the β-SiC at room temperature has been studied as shown in Figure 5 (a,b). The real part of magnetic permeability (RP) is represented by u', and Imaginary permeability (IP) part is represented by iu''. It observed that in Figure 5 (a), the maximum of value of real part permeability at frequency 14.5GHz at 2.2 and the negative value that noticed might be due to noise [22]. However, this can be explained by some noise during research, and as stated in some studies, the most crucial factor to be found is indicating through the left-hand materials (LHS) or it may initially include LHM properties. Moreover, the value of u' decrease slightly with increased frequency due to diamagnetic. The frequency dependence resonance is between the range 12.5 – 18 GHz. In other hand that, imaginary part in Figure 5(b), permeability started resonance at value of 0.027- 12.45 GHz and increased to value of 2.68 at 15.5 GHz and slightly decrease to 18GHz. Since XRD result does not observe any other impurities, the absorbed electromagnetic waves induced the ferromagnetism in β-SiC nanoparticle at room temperature, which indicated the lattice defects $V_{Si}V_C$ during the synthesis of β-SiC.

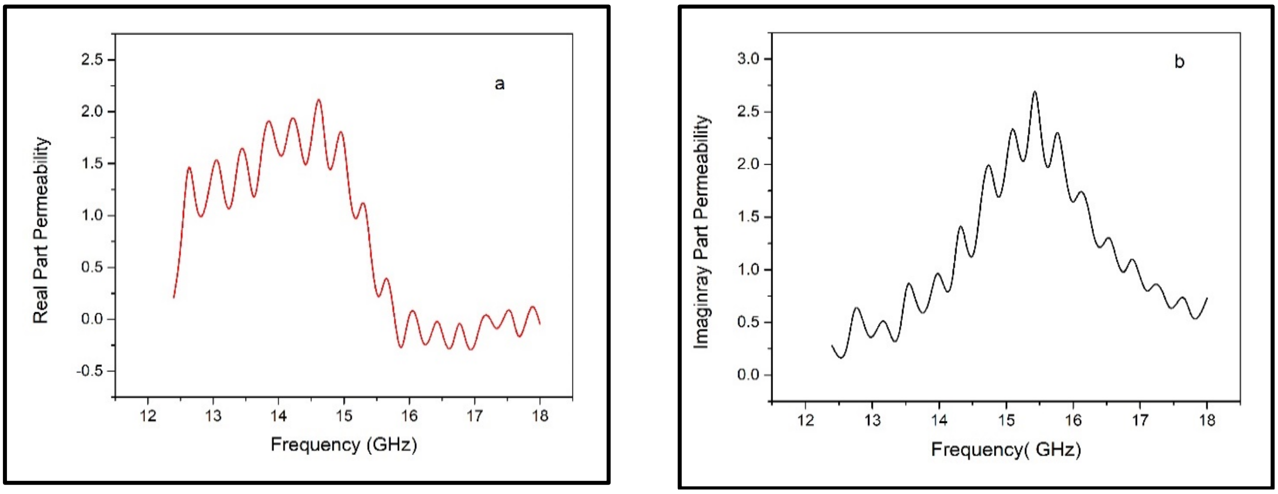


Fig. 5. EM properties of β-SiC a) RP permeability, b) IP permeability

3.4 Vibrating-Sample Magnetometer (VSM)

The *M~H* carve at room temperature shown in Figure 6 for β-SiC nanoparticle is ferromagnetic in nature. The applied magnetic field along with c-axis observes a magnetization value of 50.972E-3 emu/g with remnant magnetization is 3E-3 emu/g. Experimental data are shown by S-shape corresponding to the applied magnetics intensity. The coercivity of soft electromagnet is the probability to find the active spin in the material. In this experimental, the measured value of coercivity found to be 89.068G at squareness ratio is 0.043524. The estimated saturation of the magnetic impurities observed from the experiment is 0.00434 emu/g. The observed ferromagnetism in this material due to the defects that form in the lattice structure during synthesis.

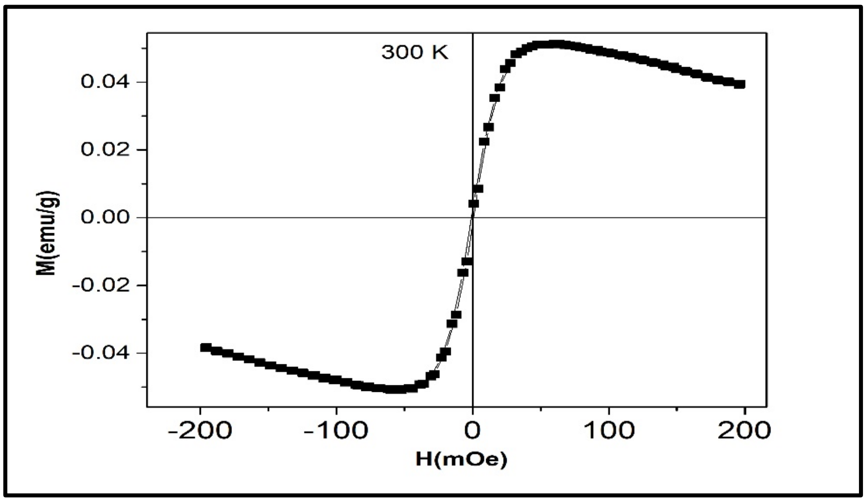


Fig. 6. Room temperature hysteresis curve of β-SiC

These defects may arise from the presence of magnetic and non-magnetic impurities, as well as contamination with oxygen. The introduction of these factors can cause a change in the hybridization of the beta-silicon carbide, specifically converting its sp^3 configuration into a mixture of sp^3 and sp^2 hybridization. This alteration in hybridization can induce ferromagnetic ordering in the material [24,25]. It has been found that 6H-SiC single crystals that have been irradiated with xenon ions exhibit long-range ferromagnetic coupling. This is thought to be due to the presence of p electrons around VsiVc divacancies in the crystal lattice, which are defects formed by the irradiation process. The nearest-neighbor carbon atoms around these divacancies are believed to be responsible for the observed ferromagnetism. [15]. Based on the lack of impurities observed in XRD data as shown in Figure 1, it is hypothesized that the natural ferromagnetism observed in β-SiC is likely a result of defects in the crystal lattice that were formed during its synthesis at high temperatures [26] after that annealing which to able to create intrinsic defect in materials [27]. The electron configuration of carbon (C) is $1s^2 2s^2 2p^2$ which requires 4 electrons to fill the highest energy p orbital. Similarly, silicon (Si) atom has an electron configuration of $1s^2 2s^2 2p^6 3s^2 3p^2$. The crystal structure of β-SiC is cubic, featuring tetrahedrally bonded Si-C bilayers with *s-p* hybridization between the orbitals of Si and C at the ground state. When Four bonds are broken to create the vacancy $V_{Si}V_C$, the nearest neighbour carbon atom lacks electrons near the broken bond, leading to the formation of two new dangling bonds and resulting in strong s-p hybridization. The observed magnetization of carbon-based materials, such as $V_{Si}V_C$, may be attributed to the presence of s-p hybridized nearest neighbour carbon atoms, which inherently possess magnetic s-p orbitals [28]. The mechanism of *s-p* magnetic carbon could offer a plausible explanation for the occurrence of room temperature ferromagnetism in these materials. Further investigation is required to establish the origin of ferromagnetism.

4. Conclusions

In summary, we investigated the magnetic properties of β-SiC nanoparticle at room temperature. Magnetic measurements revealed intrinsic ferromagnetic behaviour. The vacancies of silicon and carbon, coupled with neighboring carbon bonds of the β-SiC crystal lattice, induce a robust s-p hybridization. This hybridization, in turn, serves as the primary factor driving the development of ferromagnetism. β-SiC exhibits promising potential in the ongoing development of novel materials for spintronics applications.

Acknowledgement

We would like to extend our gratitude to Universiti Technology Petronas for their financial support through grant (015LC0-291).

References

[1] Song, B., J. K. Jian, H. Li, M. Lei, H. Q. Bao, X. L. Chen, and G. Wang. "New experimental evidence for origin of ferromagnetism ordering in Fe-doped SiC." *Physica B: Condensed Matter* 403, no. 17 (2008): 2897-2901. https://doi.org/10.1016/j.physb.2008.02.032

[2] Stromberg, F., W. Keune, X. Chen, S. Bedanta, H. Reuther, and A. Mücklich. "The origin of ferromagnetism in 57Fe ion-implanted semiconducting 6H-polytype silicon carbide." *Journal of Physics: Condensed Matter* 18, no. 43 (2006): 9881. https://doi.org/10.1088/0953-8984/18/43/010

[3] Roe, K. J., M. W. Dashiell, G. Xuan, E. Ansorge, G. Katulka, N. Sustersic, X. Zhang, and J. Kolodzey. "Ge incorporation in SiC and the effects on device performance." In *Proceedings. IEEE Lester Eastman Conference on High Performance Devices*, pp. 201-206. IEEE, 2002.

[4] Scannell, Garth, Akio Koike, and Liping Huang. "Structure and thermo-mechanical response of TiO2-SiO2 glasses to temperature." *Journal of Non-Crystalline Solids* 447 (2016): 238-247. https://doi.org/10.1016/j.jnoncrysol.2016.06.018

[5] Ledoux, Marc J., and Cuong Pham-Huu. "Silicon carbide: a novel catalyst support for heterogeneous catalysis." *Cattech* 5, no. 4 (2001): 226-246. https://doi.org/10.1023/A:1014092930183

[6] Wang, Yutian, Yu Liu, Gang Wang, Wolfgang Anwand, Catherine A. Jenkins, Elke Arenholz, Frans Munnik *et al.,* "Carbon p electron ferromagnetism in silicon carbide." *Scientific Reports* 5, no. 1 (2015): 8999. https://doi.org/10.1038/srep08999

[7] Žutić, Igor, Jaroslav Fabian, and S. Das Sarma. "Spintronics: Fundamentals and applications." *Reviews of modern physics* 76, no. 2 (2004): 323. https://doi.org/10.1103/RevModPhys.76.323

[8] Ando, Koji. "Seeking room-temperature ferromagnetic semiconductors." *Science* 312, no. 5782 (2006): 1883-1885. https://doi.org/10.1126/science.1125461

[9] Ohno, H., F. Matsukura, and Y. Ohno. "General report semiconductor spin electronics." *JSAP Int* 5, no. 4 (2002).

[10] Yazyev, Oleg V. "Magnetism in disordered graphene and irradiated graphite." *Physical review letters* 101, no. 3 (2008): 037203. https://doi.org/10.1103/PhysRevLett.101.037203

[11] Venkatesan, M., C. B. Fitzgerald, and and JMD Coey. "Unexpected magnetism in a dielectric oxide." *Nature* 430, no. 7000 (2004): 630-630. https://doi.org/10.1038/430630a

[12] Liu, Yu, Gang Wang, Shunchong Wang, Jianhui Yang, Liang Chen, Xiubo Qin, Bo Song, Baoyi Wang, and Xiaolong Chen. "Defect-induced magnetism in neutron irradiated 6 H-SiC single crystals." *Physical review letters* 106, no. 8 (2011): 087205. https://doi.org/10.1103/PhysRevLett.106.087205

[13] Červenka, J., M. I. Katsnelson, and C. F. J. Flipse. "Room-temperature ferromagnetism in graphite driven by two-dimensional networks of point defects." *Nature Physics* 5, no. 11 (2009): 840-844. https://doi.org/10.1038/nphys1399

[14] Ohldag, Hendrik, P. Esquinazi, E. Arenholz, D. Spemann, M. Rothermel, A. Setzer, and T. Butz. "The role of hydrogen in room-temperature ferromagnetism at graphite surfaces." *New Journal of Physics* 12, no. 12 (2010): 123012. https://doi.org/10.1088/1367-2630/12/12/123012

[15] Ugeda, Miguel M., Iván Brihuega, Francisco Guinea, and José M. Gómez-Rodríguez. "Missing atom as a source of carbon magnetism." *Physical Review Letters* 104, no. 9 (2010): 096804. https://doi.org/10.1103/PhysRevLett.104.096804

[16] Sultan, N. M., Thar M. Badri Albarody, Husam Kareem Mohsin Al-Jothery, Monis Abdulmanan Abdullah, Haetham G. Mohammed, and Kingsley Onyebuchi Obodo. "Thermal Expansion of 3C-SiC Obtained from In-Situ X-ray Diffraction at High Temperature and First-Principal Calculations." *Materials* 15, no. 18 (2022): 6229. https://doi.org/10.3390/ma15186229

[17] Wang, Dong-Hua, Di Xu, Qing Wang, Ya-Juan Hao, Guo-Qiang Jin, Xiang-Yun Guo, and King-Ning Tu. "Periodically twinned SiC nanowires." *Nanotechnology* 19, no. 21 (2008): 215602. https://doi.org/10.1088/0957-4484/19/21/215602

[18] Thibault, Newman W. "Morphological and structural crystallography and optical properties of silicon carbide (SiC)." *American Mineralogist: Journal of Earth and Planetary Materials* 29, no. 9-10 (1944): 327-362.

[19] Pivac, B., K. Furić, M. Milun, T. Valla, A. Borghesi, and A. Sassella. "Spectroscopic study of SiC-like structures formed on polycrystalline silicon sheets during growth." *Journal of applied physics* 75, no. 7 (1994): 3586-3592. https://doi.org/10.1063/1.356993

[20] Wang, Y-Y., K. Kusumoto, and C-J. Li. "XPS analysis of SiC films prepared by radio frequency plasma sputtering." *Physics Procedia* 32 (2012): 95-102. https://doi.org/10.1016/j.phpro.2012.03.524

[21] Makarova, T. L. "Studies of High-Temperature Superconductivity." (2003): 107.

[22] Wu, Yan, Lingfei Ji, Zhenyuan Lin, Yijian Jiang, and Tianrui Zhai. "Blue photoluminescence enhancement in laser-irradiated 6H-SiC at room temperature." *Applied Physics Letters* 104, no. 4 (2014). https://doi.org/10.1063/1.4863437

[23] Mishra, Gopa, Sankar Mohapatra, Sasmita Prusty, Manoj Kumar Sharma, Ratnamala Chatterjee, S. K. Singh, and D. K. Mishra. "Magnetic properties of nanocrystalline β-SiC." *Journal of Nanoscience and Nanotechnology* 11, no. 6 (2011): 5049-5053. https://doi.org/10.1166/jnn.2011.4109

[24] Bozack, Michael J. "Single crystal 6H-SiC (0001) by XPS." *Surface Science Spectra* 3, no. 1 (1994): 82-85. https://doi.org/10.1116/1.1247767

[25] Raju, Mula, Supriti Sen, Debasish Sarkar, and Chacko Jacob. "Synthesis of 3C-silicon carbide 1D structures by carbothermal reduction process." *Journal of Alloys and Compounds* 857 (2021): 158243. https://doi.org/10.1016/j.jallcom.2020.158243

[26] Jiang, M., D. D. Wang, B. Zou, Z. Q. Chen, A. Kawasuso, and T. Sekiguchi. "Effect of high temperature annealing on defects and optical properties of ZnO single crystals." *physica status solidi (a)* 209, no. 11 (2012): 2126-2130. https://doi.org/10.1002/pssa.201127527

[27] Fan, X. F., L. Liu, R. Q. Wu, G. W. Peng, H. M. Fan, Y. P. Feng, J. L. Kuo, and Z. X. Shen. "The role of sp-hybridized atoms in carbon ferromagnetism: a spin-polarized density functional theory calculation." *Journal of Physics: Condensed Matter* 22, no. 4 (2010): 046001. https://doi.org/10.1088/0953-8984/22/4/046001