Impact of Irradiation on the Crystallization and Electrical Properties of Bismuth-Based Superconductors at High Temperatures

Hanen Majeed Rashed[1], Niran Abeduljabbar[1] and Abdul Karim Ali[2]
[1]*Department of Physics, College of Education for Pure Sciences, Tikrit University, 34001 Tikrit, Iraq*
[2]*Department of Physics, College of Sciences, Tikrit University, 34001 Tikrit, Iraq*
aa230072ued@st.tu.edu.iq, niran.fadhil64@tu.edu.iq, abdelkareemdahash2290@gmail.com

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Abstract: The superconducting compound $Bi_{2(x+y)}\ Ag_xCd_yBa_2\ Ca_2\ Cu_3\ O_{10+\delta}$ was studied using the solid-state reaction method at an annealing temperature of 850°C and under a pressure of 8 tons/cm² applied by a hydraulic press in the presence of sufficient oxygen. These conditions are considered ideal based on previous research for preparing high-performance electric superconductors with different compensation ratios (x, y). It was found that compensation at x = 0.3 and 0.4 led to a decrease in the critical temperature (Tc) to 136 K and 134 K, respectively, due to a reduction in the length of the c-axis, which negatively affected Tc. An increase in the compensation ratio y = 0.4 also resulted in a decrease in Tc to 140 K, accompanied by changes in the crystal structure of the compound. X-ray diffraction (XRD) studies showed an increase in the c-axis length to 36.525 Å at x = 0.3 with a = b = 5.358 Å, and similarly, an increase in the c-axis length to 37.215 Å at y = 0.3 with a = b = 5.314 Å.

1 INTRODUCTION

Superconductivity is a unique physical phenomenon characterized by the ability of some materials to conduct electricity without any resistance at very low temperatures.[1]. When these materials reach a certain critical temperature, they become superconductors, meaning they can conduct electricity without losing energy. A unique property of these materials is the Meissner effect [2], where magnetic fields are repelled from within them, causing them to float above magnets. Research in this area is exciting, especially since superconductors operate at higher temperatures, making their applications easier. Superconductivity is used in many applications [3], such as magnetic levitation trains that rely on levitation to reduce friction and increase speed, and magnetic resonance imaging (MRI) devices that take advantage of strong magnetic fields. This phenomenon contributes to new innovations in many fields, making superconductivity a vital topic in science and technology [4].

The phenomenon of superconductivity was first discovered by the scientist Heike Kamerlingh Onnes in 1911, when he measured the resistance of pure mercury at liquid-helium temperatures. He observed that the electrical resistance of mercury suddenly dropped to less than $10^{-5}\ \Omega$ at a temperature of about 4.2 K. This unexpected collapse of electrical resistance indicated that the material could carry an electric current without any dissipation. The temperature at which a material undergoes the transition from the normal state to the superconducting state is called the critical temperature (Tc) [6], [7]. The value of Tc varies from one material to another. In practice, superconductivity is characterized by two reference points: the onset temperature, where the resistivity starts to decrease, and the zero-resistance temperature (T_o), which marks the completion of the transition – the difference between them being the transition width.

Onnes was the first scientist to discover this remarkable phenomenon, for which he was deservedly awarded the Nobel Prize in Physics in 1913. Since then, research interest in superconductivity has grown tremendously, particularly in the search for new materials with higher Tc values due to their great industrial and technological importance. This discovery eventually formed the basis of the Bardeen–Cooper–Schrieffer (BCS) theory.

In 1957, a groundbreaking theory explained superconductivity at the quantum level, proposing that the formation of electron pairs – known as Cooper pairs - plays a fundamental role in the phenomenon [8], [9].

2 PRACTICAL PART

2.1 Calculation of Elemental Weights

The weight ratios of the materials (w1–w5) were measured using a high-sensitivity electronic balance (SCALTEC Instruments LLC, accuracy ±0.0001 g).

2.2 Heat Treatment

Heat treatment is the process of treating certain materials (often metals) by applying specific temperatures for specific periods of time, with the aim of improving their physical or chemical properties. These properties include hardness, strength, ductility, and flexibility.

Annealing is a special type of heat treatment, which aims to reduce internal stresses in the metal and increase its ability to form. The process is done by heating the metal to a specific temperature and then cooling it slowly.

2.3 Measurement of Electrical Resistance of Samples as A Function of Temperature

Measuring the electrical resistivity of a superconducting material requires special conditions due to its unique nature. When a material is in a superconducting state, its electrical resistance is close to zero.

Resistance can be found using the following relationship:

$$R = \frac{V}{I}\,. \qquad (1)$$

Where R she the resistance for sample, A - the Cross-sectional area of sample, l - the length of the sample between the two points of potential difference [10]:

$$\rho = \frac{RA}{l}. \quad \dots \qquad \dots (2)$$

2.4 X-ray Diffraction XRD

X-ray examination (XRD) is a technique used to analyze the crystal structure of materials. Here are the steps for a check

- choice: the sample should be solid and suitable for examination.

Grinding: grind the sample into fine particles to improve distribution.

Packing: packing the sample in a suitable holder. Device settings: Make sure the device is working correctly and calibrated.

Determining the drop angle: adjusting the drop angle for X-rays (usually 0-90 degrees). X-rays: X-rays are directed toward the sample.

3 RESULTS AND DISCUSSION

3.1 Study of the Electrical Properties of Modified Bi-Based High-Temperature Superconductors

The electrical properties of $Bi_{2(x+y)}$ $Ag_xCd_yBa_2$ Ca_2 Cu_3 $O_{10+\delta}$ were studied at different ratios of x, with x=0.1, x=0.2, x=0.3, and x=0.4. The results showed that the critical temperature (Tc) rose to 135 K at x=0.1, and further increased to 144 K at x=0.2. This rise in Tc is due to an ideal degree in the crystal structure of the compound, where increasing the oxygen ratio with increasing the concentration improves the crystal arrangement, increasing the Tc. However, when the ratio increased to x=0.3 and x=0.4, the Tc decrease was observed to 136 K and 134 K, respectively , As in the Figure 1. This decline is due to an increase in the length of the c-axis, which leads to changes in the crystal structure of the compound when the ratio exceeds 0.2. To understand these results more deeply, we can draw on several models and theories. First, the conduction band model explains how the crystal structure affects the bandwidth of the conduction band and the position of the bands. As the X ratio increases, conductivity properties can improve due to increased levels of energy available to electrons, resulting in a rise in Tc.

Second, Bose-Einstein Condensation's theory shows how oxygen atoms condense into crystal structure and increase the effective number. As oxygen increases, the number of electrons contributing to condensation formation increases, contributing to an increase in Tc. Third, Joule Heating's model highlights the effect of impurities and various structures on resistance. With an increase in the ratio (x), impurities may reduce resistance and increase Tc initially, but after a certain point, these impurities begin to negatively affect conductivity. Fourth, spectroscopy can be used to determine the crystal arrangement and its effect on electrical properties. This analysis helps illustrate how crystal arrangement affects electrical properties and contributes to an increase in Tc. Finally, molecular dynamics models allow simulates interactions between atoms and their effect on TC, showing how changes in crystal structure lead to changes in electrical properties.

Based on the above, the results indicate that changes in crystal structure profoundly affect superconductivity properties, enhancing the understanding of the complex relationships between structure and properties and contributing to the improved design of new materials with improved electrical properties [1].

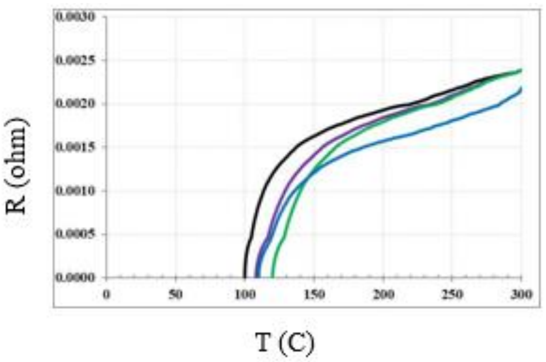

Figure 1: The relationship between the resistivity and the critical temperature of a compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ When you are x=0, 0.1, 0.2, 0.3, 0.4.

The electrical properties of the compound $Bi2_y$ CdyBa2Ca2Cu3O10+δ were studied at different proportions of (y), where the values were y=0.1, y=0.2, y=0.3, and y=0.4. The results, as shown in Figure 2, showed that the critical temperature (Tc) swas 152 K at y=0.1, with an oxygen ratio of 10.25. When the ratio increased to y=0.2, the critical temperature rose to 158 K with an oxygen ratio of 10.28. These results can be explained by the fact that the compound achieved an ideal degree in the crystal structure. The replacement of part of the CD element with the Bi element in the compound led to an increase in critical temperature, as well as an increase in the percentage of oxygen as the concentration increased, which contributed to the raising of the Tc.

However, when the ratio was increased to y=0.3, a decrease of Tc to 146 K with an oxygen ratio of 10.20 was observed. The critical temperature also dropped to 140 K at y=0.4. This decline is attributed to an increase in the length of the c-axis, which leads to changes in the crystal structure of the compound, which negatively affects the Tc, as in the Figure 2. These results are consistent with previous studies suggesting that an increase in the length of the C-axis leads to a decrease in critical temperature. These results also show the good order and order observed in the structure of the superconductor, which enhances our understanding of the relationship between crystal structure and electrical properties.

The results reflect the impact of changes in Y ratio on superconductivity properties, enhancing the understanding of the complex relationships between composition and properties, contributing to the improved design of new materials with improved electrical properties.[12].

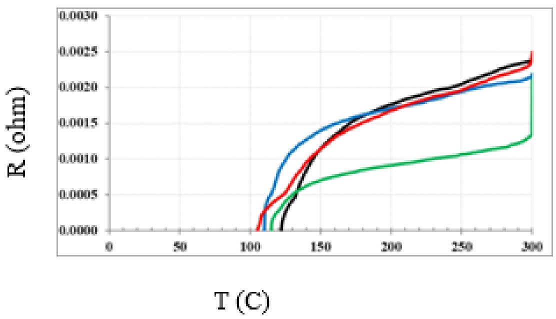

Figure 2: The relationship between the resistivity and the critical temperature of a compoundBi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ When y =0, 0.1, 0.2, 0.3, 0.4.

3.2 Study of the Structural and Volumetric Properties of Bi-Based Cuprate Superconductors

The structural properties of the compound Bi2_xAgxBa2Ca2Cu3O10+δ were studied at a ratio of (x=0.1) below the annealing temperature of 850 °C. The study of X-ray diffraction (XRD) showed uniformity in the crystal structure, with clear peaks appearing. After applying Brack's law, HKL values were determined that express the distance between parallel planes. From the angles of reflection, Miller's coefficients (HKL) were reached. Using special software, the dimensions of the cell unit were found, where they were (c=34.423 Å) and (a=b=5.341 Å), indicating that they are of the right quadrilateral type, as in the Figure 3.

At substitution (x=0.2), an increase in the intensity and regularity of the peaks, retaining the type of crystal structure, and an increase in the length of the c-axis to (c=35.513 Å) and (a=b=5.425 Å) were observed, as in the Figure 4. The study of X-ray diffraction showed prominent and clear peaks, demonstrating an improvement in the crystalline structure. As the ratio increased to (x=0.3), the length of the c-axis increased again, with dimensions (c=36.525 Å) and (a=b=5.358 Å), as in the Figure 5. However, at the ratio (x=0.4), a decrease in the intensity of the peaks was observed, indicating a decrease in the regularity of the crystal. The lattice dimensions were (c=34.932 Å) and (a=b=5.486 Å), with a clear decrease in the length of the c-axis, as in the Figure 6. As for the study of the structural properties of the variable (y), the structural properties of the compound Bi2_yCdyBa2Ca2Cu3O10+δ were studied at a ratio of (y = 0.1) at a annealing temperature of 850 ° C. The study of X-ray diffraction (XRD) showed uniformity in the crystal structure and the appearance of pronounced peaks. After the application of Brack's law, DHK values expressing the distance between parallel planes were determined, and Miller's coefficients (HKL) were reached. The dimensions calculated for the cell unit showed (c=34.534 Å) and (a=b=5.432 Å), indicating that it is of the right quadrilateral type, as in the Figure 7.When the ratio increased to (y=0.2), an increase in the intensity and regularity of the peaks was observed, with an increase in the length of the c-axis to (c=35.215 Å) and (a=b=5.453 Å), as in the Figure 8. The X-ray diffraction study indicated an improvement in crystalline structure, showing more pronounced peaks. At (y=0.3), the length of the c-axis increased again, with dimensions (c=37.215 Å) and (a=b=5.314 Å), as in the Figure 9. However, at (y=0.4), a decrease in the intensity of the peaks was observed, indicating a decrease in the regularity of the crystal. The dimensions of the lattice were (c=36.427 Å) and (a=b=5.442 Å), with a clear decrease in the length of the c-axis, as in the Figure 10.

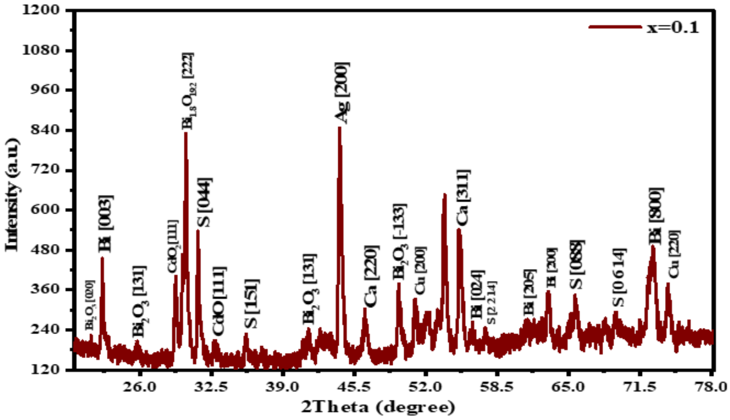

Figure 3: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ when X=0.1.

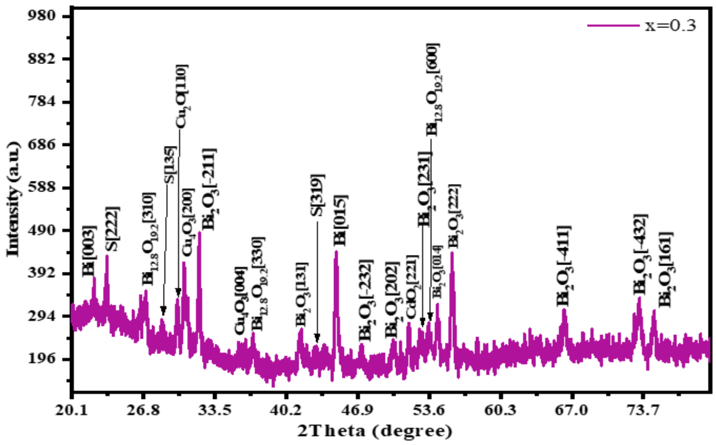

Figure 4: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ when X=0.2.

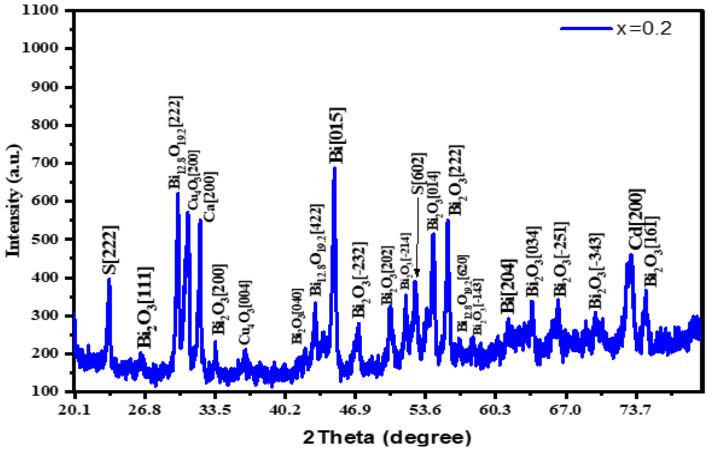

Figure 5: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ when X=0.3.

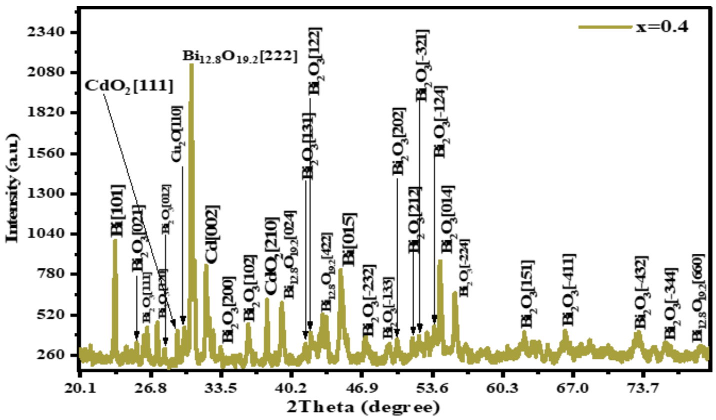

Figure 6: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ When X=0.4.

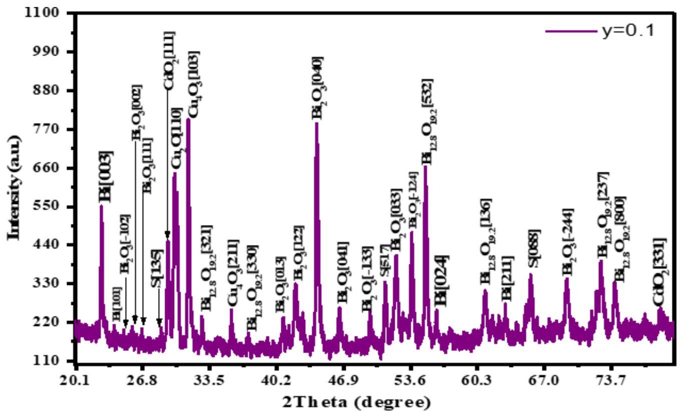

Figure 7: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ when y=0.1.

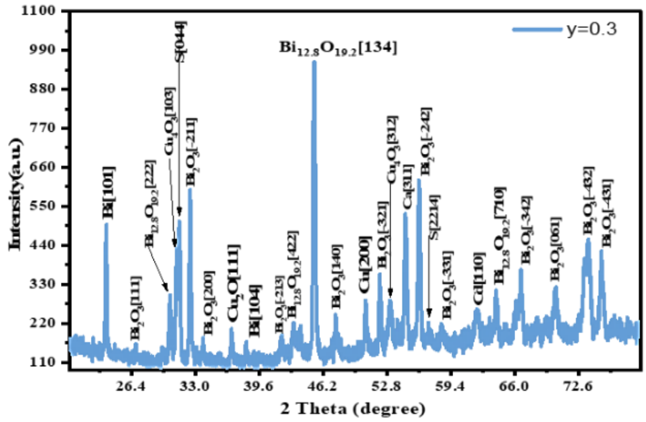

Figure 8: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ When y=0.2.

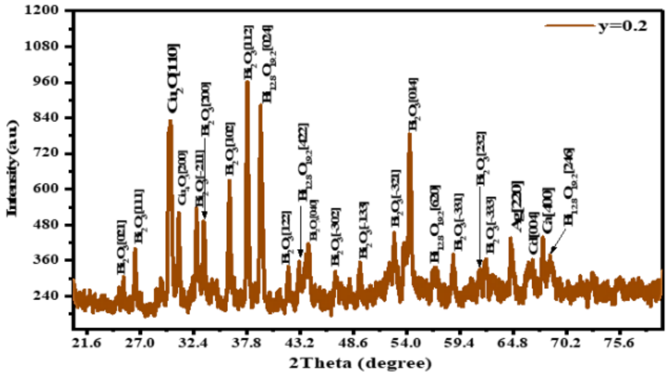

Figure 9: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ When y=0.3.

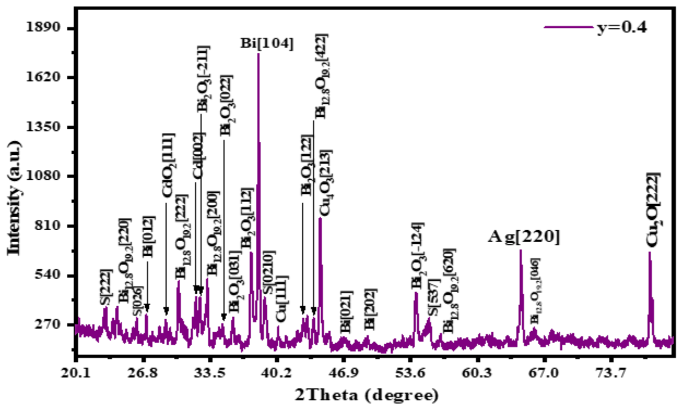

Figure 10: X-ray diffraction of the compound Bi2(x+y) AgxCdyBa2 Ca2 Cu3 O10+δ when y=0.4.

CONCLUSIONS

This study included preparing samples of the compound at a temperature of 850°C and an electrostatic pressure of 800 MPa. These are ideal conditions for preparing samples to obtain the greatest possible degree of regularity in the crystal structure and to reach the best critical temperature, and with partial replacement of the Ag element in the Bi element, at different ratios (x=0.1, 0.2, 0.3, 0.4). If complete regularity is achieved in the crystal structure with an increase in the length of the c axis, then when substituting x = 0.2 the critical temperature becomes 144 K. When partially substituting the Cd element in the Bi element in different ratios (y = 0.1, 0.2, 0.3, 0.4) the best ratio is y = 0.2, so the temperature becomes 158 K . The percentage of oxygen helps the crystals to be organized in the Cu-O planes, and therefore the crystal structure will be improved regularly and the length of the c-axis will increase. The critical temperature increases with the increase in the regularity of the crystal structure, and it is not constant but depends on the preparation conditions. In the future, elements can be replaced with other elements to obtain a better value for the critical temperature, and other methods can be used to obtain structural and electrical properties.

REFERENCES

[1] S. Y. Arachchige, "Non-local electrodynamics of superconducting wires: implications for flux noise and conductance," M.Sc. thesis, Univ. of Victoria, 2017.

[2] A. Cubero, et al., "Effects of laser-induced periodic surface structures on the superconducting properties of Niobium," Appl. Surf. Sci., vol. 508, p. 145140, 2020, [Online]. Available: https://doi.org/10.1016/j.apsusc.2020.145140.

[3] O. Erdem and E. Yanmaz, "Effect of laser irradiation on activation energy, irreversibility field and upper critical magnetic field of bulk MgB_2 superconductor," J. Mater. Sci.: Mater. Electron., vol. 27, pp. 6502-6510, 2016, [Online]. Available: https://doi.org/10.1007/s10854-016-4624-1.

[4] N. A. Abdul Wahid, "Effect of the Laser on the structural and electrical properties of the compound $Tl_{2-x}Hg_xBa_2Ca_2Cu_3O_{10+\delta}$," M.Sc. thesis, Univ. of Tikrit, 2016.

[5] K. A. Gschneidner, Jr., L. Exring, and M. B. Mapale, Handbook on the Physics and Chemistry of Rare Earths, vol. 30, Elsevier Science, 2000.

[6] A. S. Karim, Z. N. Majeed, and S. Y. Darweesh, "The effect of nanostructured zirconia reinforcement on the mechanical and structural properties of a copper-based system," Materials Science Forum, vol. 1039, pp. 297-306, Aug. 2021, [Online]. Available: https://doi.org/10.4028/www.scientific.net/MSF.1039.297.

[7] E. T. Khalil, "Effect of the laser on the structural and electrical properties of the compound $TL_{2-x}Ag_xBa_2Ca_2Cu_3O_{10+\delta}$," M.Sc. thesis, Univ. of Tikrit, 2017.

[8] O. A. Gitan, "Effect of partial substitution of (Pd, Cd) on structural and electrical properties of ($Bi_2Ba_2Cu_3O_{10+\delta}$) high temperature superconductor," M.Sc. thesis, Univ. of Tikrit, 2014.

[9] C. H. A. Zaynal, "Effect of the laser and repeated annealing on the synthetic structural and electrical properties of the compound $Bi_{2-(X+Y)}Pd_xAg_ySr_2Ca_2Cu_3O_{10+\delta}$," M.Sc. thesis, Univ. of Tikrit, 2018.

[10] S. S. A. Ali, A. K. D. Ali, and S. J. Fathi, "Nano oxides addition effect on the characteristic of high temperature $Hg_{1-x}Pb_xBa_2Ca_{3-y}Mg_yCu_4O_{10+\delta}$ superconductors," Ph.D. thesis, Univ. of Tikrit, 2019.

[11] N. A. Ghazal, Z. N. Majeed, and S. Y. Darweesh, "The effect of adding different percentages manganese on some mechanical and magnetic properties of composite (Al-Cu)," AIP Conference Proceedings, vol. 2885, no. 1, Mar. 2024, [Online]. Available: https://doi.org/10.1063/5.018224.