VIETNAM NATIONAL UNIVERSITY
HANOI UNIVERSITY OF SCIENCE

Duong Thi Thanh Nhan

INVESTIGATION OF THE CRYSTAL STRUCTURE AND CRITICAL PARAMETERS OF MgB_2 SUPERCONDUCTORS THROUGH ADDITION AND ION IRRADIATION

Major: Thermal Physics
Code: 9440102.07

ABSTRACT OF DISSERTATION FOR
DOCTOR OF PHYLOSOPHY IN PHYSICS

Hanoi - 2026

The dissertation has been completed at: University of Science, Vietnam National University, Hanoi.

Scientific supervisor: Assoc. Prof. Dr. Tran Hai Duc

Reviewer:

Reviewer:

Reviewer:

The dissertation will be defended before the Doctoral Dissertation Evaluation Committee, convened at the University of Science, Vietnam National University, Hanoi, on:

Information about the dissertation can be found at:

-The National Library of Vietnam;

-The Library and Digital Knowledge Center, Vietnam National University, Hanoi.

INTRODUCTION

a. Rationale for the study

MgB_2 is a superconductor with T_c ~ 39 K, holding considerable promise for practical superconducting applications. However, the widespread deployment of this compound in high field remains limited by two principal challenges: the rapid degradation of the critical current density (J_c) arising from weak flux pinning, and the relatively low value of the upper critical magnetic field (B_{c2}). This research focuses on enhancing the superconducting performance, and in particular on improving the J_c so as to render the material suitable for practical applications.

b. The purpose, objectives, and scope of the research

This research aims to enhance the critical parameters of MgB_2 superconductors, thereby improving their properties for high-field performance, particularly in next-generation wires and tapes. To achieve this, the study employs a dual-track approach to comprehensively evaluate and contrast bulk and thin-film forms, aiming to overcome current material limitations.

The principal subjects of the study are (SiC + Mg) co-added bulk MgB_2 superconductors and pristine MgB_2 superconducting thin films fabricated by the hybrid physical - chemical vapor deposition (HPCVD) method and subsequently irradiated with Nb and Ni ions.

The scope of the study is confined to a single superconducting compound, MgB_2, and is strictly limited to two branches of processing: co-addition of SiC and Mg for the bulk samples, and ion irradiation (Nb and Ni) within a safe energy range for the thin films. The evaluation is limited to the microstructural crystal dynamics, the

surface morphology (for the films), and the in-field superconducting performance at the critical state.

c. The scientific novelty

Understanding bulk modification mechanisms: to provide experimental evidence that co-addition (SiC + Mg) enhances the intrinsic superconducting performance and the flux pinning of bulk MgB_2 material.

Characterization of thin-film defect dynamics: to explore the role of physical defects created by Ni and Nb ion bombardment in enhancing the superconducting characteristics of high-purity, HPCVD-grown MgB_2 thin films.

Understanding the vortex pinning mechanism: to offer a balanced view of the pinning mechanisms by studying co-addition in bulk samples and irradiation in thin films, thereby assessing the extent to which these complementary techniques constrain vortex motion in high fields.

Advancing theoretical understanding: this work provides crucial data supporting the development of MgB_2 superconductors for practical applications, informing the production of superconducting wires and tapes for use in MRI machines and in superconducting cables for electric-power transmission.

d. New findings of the thesis

+ Remarkable retention of the T_c after addition or irradiation: The simultaneous addition of Mg and SiC to bulk MgB_2 samples by the solid-state reaction method preserved T_c above 37 K (approximately equal to that of the pure sample and to the theoretical value of 39 K). The T_c of MgB_2 thin-films were maintained above 32 K after irradiation. There were impressive results in maintaining T_c

compared with domestic and international studies, overcoming the common disadvantage of the sharp reduction in T_c encountered upon chemical addition or irradiation.

+ *Discovery of a shift in the flux-pinning mechanism through ion irradiation:* It was demonstrated that a partial shift of the pinning mechanism from **normal surface pinning** to **normal point pinning** occurs in the high-magnetic-field region in MgB_2 thin films after Nb and Ni ion irradiation.

+ *Discovery of relatively strong pinning induced by Ni ions:* Ni ion irradiation produced a transition from a weak-pinning to a relatively strong-pinning mechanism. At 5 K, the pinning strength in the sample irradiated with a dose of 3×10^{13} ion/cm² yielded $\beta = 0.67$ (approaching the theoretical value of $\beta = 5$ for the strong-pinning).

+ *Elucidation of the stronger J_c enhancement via ion tracks:* It was established that Ni ion irradiation yields a stronger enhancement of the critical current density J_c in high magnetic fields than Nb ion irradiation. The dissertation clarified that the origin of this phenomenon lies in the higher and more uniform density of point defects within the film, in the form of **ion tracks** and lattice distortion.

+ *Precise determination of the irradiation-dose thresholds yielding the best J_c enhancement:* The dissertation identified the precise quantitative values yielding the optimal J_c enhancement for each ion species in 400-nm-thick MgB_2 thin films (fabricated by HPCVD): **for Nb ions (1 MeV)**, the optimal dose is 7×10^{13} ion/cm²; **for Ni ions (1 MeV)**, the optimal irradiation dose is 3×10^{13} ion/cm². In both cases T_c is maintained above 30 K, entirely suitable for practical applications without the need for liquid-helium cooling.

Chapter 1. LITERATURE OVERVIEW

This chapter presents a brief history of the more than 100 years of development in the field of superconductivity. Over more than a century, numerous theories, models, and materials have been reported, including the London equations, the BCS theory, and the Dew-Hughes model, among others. The dissertation focuses on introducing the critical parameters, properties, and mechanisms occurring in type-II superconductors, in which the magnetic flux penetrating this class of superconductor exists in the form of vortices.

Chapter 1 also provides an overview and research history of MgB_2 material, focusing on its simple crystal structure and its unique superconducting properties. The advantages and limitations, the research directions for this class of superconductor, and its application prospects are also presented.

The dissertation carefully examined the latest publications in the field of MgB_2 research and identified the material's greatest limitation for applications as the maintenance of J_c under high-magnetic-field conditions. Maintaining J_c in a high magnetic field requires a pinning force acting on the vortices so that they do not move when an electric current passes through the superconductor.

Based on recent domestic and international studies, the dissertation synthesized and classified four research directions for improving the critical parameters, particularly the critical current density J_c - the most important critical parameter for the practical application of MgB_2 - as follows:

+ *For bulk MgB_2:* There are two common methods for improving the superconducting properties: (1) Doping: the addition of

other substances to modify the superconductivity by altering the flux-pinning mechanism in the material; in some cases, doping with carbon and carbon-bearing compounds gives rise to an improvement in J_c; (2) Irradiation: studies of ion irradiation of the samples, most of which yielded no result owing to the irradiation range being too small relative to the sample thickness.

+ *For thin-film MgB_2:* There are two methods for improving the superconducting properties: (1) Creation of a buffer layer within the film; this method mainly improves T_c, whereas J_c decays rapidly as the magnetic field increases; (2) Irradiation: acting on the crystal structure of the film to produce distortions, lattice disorder, or defects that modify the superconducting properties, and many studies have reported an improvement in J_c.

On the basis of the fundamental studies of MgB_2 material and the research directions pursued worldwide, the dissertation set out its main objectives, subjects, and scope, the foremost objective being the improvement of the critical current density J_c.

Chapter 2. EXPERIMENTS

2.1 Sample fabrications

The bulk MgB_2 samples were fabricated by the solid-state reaction method, using commercial MgB_2 powder, Mg powder, and SiC powder (Alfa Aesar, 99.0% purity).

The pure MgB_2 thin films used in the dissertation were fabricated by the hybrid physical–chemical vapor deposition (HPCVD) method.

The ion irradiation process was simulated using the licensed, dedicated software Stopping and Range of Ions in Matter (SRIM).

The thin films were irradiated with Nb and Ni ions using an accelerator with an ion-beam energy of 1 MeV and doses varying over 3×10^{13}, 5×10^{13}, 7×10^{13}, and 9×10^{13} ion/cm². The sample series used in the dissertation are listed in Tables 2.1 and 2.3.

Table 2.1. *Bulk MgB_2 samples and fabricated conditions*

No.	Bulk sample	Sintering
1	Pristine	(900 °C – 1 hour)
2	Mg + MgB_2	(900 °C – 1 hour)
3	5 wt% SiC + Mg + MgB_2	(900 °C – 1 hour)
4	10 wt% SiC + Mg + MgB_2	(900 °C – 1 hour)
5	15 wt% SiC + Mg + MgB_2	(900 °C – 1 hour)
6	20 wt% SiC + Mg + MgB_2	(900 °C – 1 hour)

Table 2.3. *Ni-ions and Nb-ions irradiated MgB_2 and ion doses details*

No.	Dose (ion/cm^2)	Film name	Film name
1	0	Pristine	Pristine
2	3×10^{13}	Ni-3E13	Nb-3E13
3	5×10^{13}	Ni-5E13	Nb-5E13
4	7×10^{13}	Ni-7E13	Nb-7E13
5	9×10^{13}	Ni-9E13	Nb-9E13

2.3 Sample investigations

The crystal structure was investigated by X-ray diffraction (XRD); the surface morphology by atomic force microscopy (AFM);

the resistivity was measured as a function of temperature; and the magnetization was measured using a PPMS system. The crystal-lattice vibrations and the electron–phonon coupling were investigated by Raman spectroscopy.

Chapter 3. ENHANCEMENTS OF SUPERCONDUCTING PROPERTIES IN MgB_2 BY CO-ADDITION OF Mg AND SiC

3.1 Investigation of T_c in (SiC + Mg + MgB_2) bulks

The study showed that when only Mg was added, T_c retained its highest value in the sample; the addition of SiC led to a reduction of the T_c values relative to the pristine sample, a reduction stemming from the poorer crystalline perfection and the reduced grain size.

However, the decrease of only about 1 K after co-addition is a noteworthy result, indicating the ability to maintain a relatively high T_c after addition.

3.2 Enhancements of B_{c2} of (SiC + Mg + MgB_2) bulks

B_{c2} increased most in the (Mg + MgB_2) bulk sample, reaching 15.82 T. As the amount of SiC added to the sample increased, B_{c2} tended to decrease from 15.72 T (for 5wt.% SiC) to 15.12 T (for 20% SiC). This decrease is a consequence of the increased impurity concentration and the enhanced intraband and interband scattering in the material. Nevertheless, despite this decrease, the B_{c2} value always remained higher than that of the pristine material.

Table 3.2. *T_c and B_{c2} of pure and (SiC + Mg + MgB_2) bulks*

No.	Bulk sample	T_c (K)	B_{c2} (T)
1	Pristine MgB_2	38.09	14.64
2	Mg + MgB_2	38.57	15.82

No.	Bulk sample	T_c (K)	B_{c2} (T)
3	5 wt% SiC + Mg + MgB_2	37.83	15.72
4	10 wt% SiC + Mg + MgB_2	37.64	15.42
5	15 wt% SiC + Mg + MgB_2	37.37	15.65
6	20 wt% SiC + Mg + MgB_2	37.12	15.12

3.3 Enhancements of J_c in (SiC + Mg + MgB_2) bulks

The J_c values were determined from the magnetic hysteresis loops measured at various temperatures by applying the modified Bean model for bulk samples. The results showed that the addition of 0.5 mol Mg improved J_c (relative to the pure sample). The co-addition of 0.5 mol Mg with 5 wt%, and subsequently 10 wt%, SiC further improved the J_c value. However, when the SiC content increased beyond a threshold (15% and 20%), J_c enhanced at all temperatures.

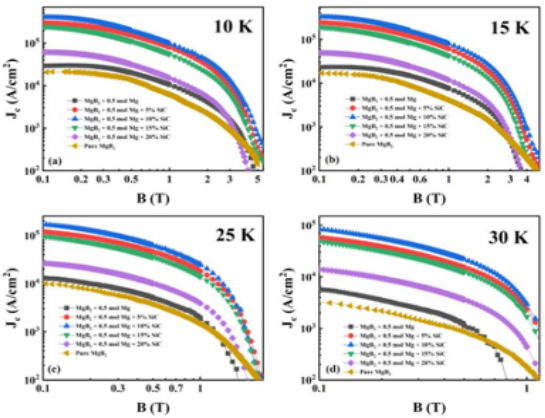


Figure 3.4. *J_c of pure and (SiC + Mg + MgB_2) bulks at 10 K, 15 K, 25 K, and 30 K*

3.4 Pinning mechanism in the pure and (SiC + Mg + MgB_2) bulks

Fitting the data to the Dew-Hughes model yielded $b_{peak} \approx 0.22$ and $p \approx 0.65$, confirming a surface-core pinning mechanism occurring at the grain boundaries, in which the sample containing 10% SiC optimized this effect through improved coupling between grain boundaries, consistent with the maximum J_c enhancement being achieved in the sample containing 10% SiC. The pinning mechanism was also investigated using the model specific to bulk materials, and the results showed that the dominant pinning mechanism after co-addition is normal surface pinning. This result is fully consistent with the analysis based on the Dew-Hughes model for bulk MgB_2.

Chapter 4. INVESTIGATION OF THE CRYSTAL STRUCTURE AND SUPERCONDUCTING PROPERTIES IN MgB_2 BY IRRADIATION OF NIOBIUM IONS

4.1 Simulation of the Nb-irradiation processes

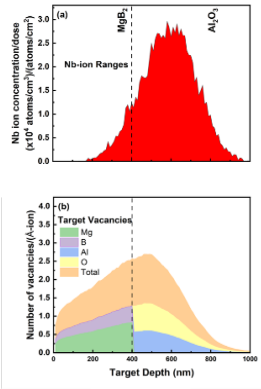


Figure 4.1. *(a) Mean projected range and (b) vacancy depth profile for 1MeV Nb-ion irradiated MgB_2 film on c-axis-cut Al_2O_3 substrate.*

Simulation saves considerable cost and time in the experiments and also enables prediction of the phenomena occurring within the sample. Using the licensed SRIM software, the irradiation of the MgB_2 films (400 nm thick, density 2.57 g/cm³) with 1 MeV Nb ions was simulated. The results showed that most of the Nb ions stop at the film–substrate interface region (approximately 600 nm). This gives rise to lattice distortion and disorder, which may alter the superconducting properties as the Mg and B atoms are displaced or replaced by Nb ions.

4.2 Variations of the crystal structure in MgB_2 films before and after irradiation by Nb ions

4.2.1 XRD analysis

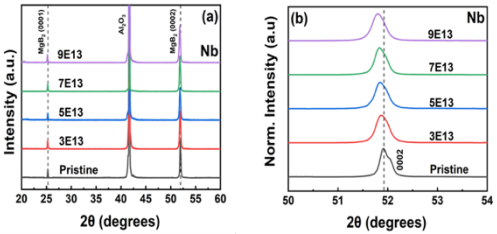


Figure 4.2. *XRD diagram of the pristine and Nb-ion irradiated MgB_2 films*

The XRD patterns confirmed that the hexagonal crystal structure of the MgB_2 film was stably maintained without any complete recrystallization phase transition or phase breakdown, even under the highest Nb ion dose. The intensity of the (0002) diffraction peak, originally very high, was markedly reduced and broadened. The full width at half maximum (FWHM) of the (0002) peak increased from 0.26° to 0.32°, evidencing a gradual reduction in crystallinity

owing to lattice disorder. The shift of the diffraction peaks toward lower 2θ angles reflects an expansion of the interplanar spacing along the *c*-axis. The *c*-axis lattice parameter, calculated on the basis of the hexagonal crystal structure, increased from 3.5210 Å (for the pristine sample) to a maximum of 3.5277 Å at a dose of 7×10^{13} ion/cm², and then decreased slightly to 3.5245 Å at the highest ion dose. The lattice strain was also investigated and was found to increase monotonically with the irradiation dose.

4.2.2 Investigation of the surface morphology before and after irradiation

The AFM images showed that, upon Nb ion irradiation at a dose of 5×10^{13} ion/cm², the surface structure of the pristine film was altered such that the grain boundaries could no longer be clearly identified. The direct images only allow the inference of the possible formation of locally disordered regions and internal defects that act as pinning centers within the film.

4.2.3 Crystal structure variations of pristine and Nb-ion irradiated MgB_2 films

For the pristine film, this peak is centered at 600.87 cm^{-1}. As the Nb ion dose increased, the E_{2g} peak shifted toward lower wavenumbers. At the maximum dose, the peak position and the full width at half maximum (FWHM) decreased to their minimum values. The narrowing of the E_{2g} peak indicates that the reduction in the EPC strength outweighed the spectral-broadening effect due to lattice disorder. The increase in the intensity of the ω_3 peak indicates an increasing degree of lattice disorder and simultaneously reflects a contribution from the phonon density of states (PDOS) owing to the relaxation of the Raman selection rules.

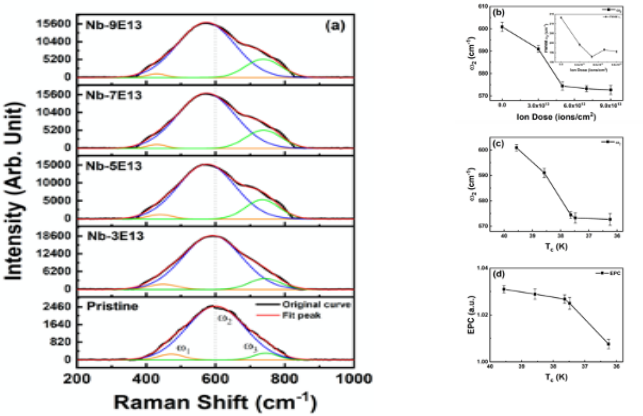


Figure 4.4. *Raman spectroscopy and parameter analysis of pristine and Nb-irradiated MgB_2 films*

The EPC values also help to distinguish the contributions of the σ and π energy bands. Previous studies have shown that the EPC values for the σ and π bands are approximately 1.02 and 0.45, respectively. The EPC values obtained confirm that the σ band is the dominant contributor to superconductivity in both the pristine film and the Nb-ion-irradiated MgB_2 thin films. Based on the McMillan formula, the electron–phonon coupling constant (EPC, λ) was found to decrease from 1.0310 (for the pristine sample) to 1.0289 and 1.0076, respectively, with increasing irradiation dose. The decrease in λ correlates directly with the reduction of T_c in the irradiated thin films.

4.4 Superconductivity of pristine and Nb-ion irradiated MgB_2 films

4.4.1 Retention of a high critical temperature T_c

Increasing the Nb ion dose led to a gradual reduction of T_c and a continuous broadening of the superconducting transition region. This

reduction may originate from the increased degree of disorder, the higher defect density, the weakening of intergrain coupling, and the thermal activation of vortices induced by the ion bombardment. Nevertheless, this reduction of T_c is relatively small, remaining close to the T_c value of the pristine film.

Table 4.5. *T_c values of the film before and after Nb ion irradiation*

Film	T_c (K)	T_c (Nb-ions) / T_c (pristine) (%)
Pristine	39.56	100
Nb-3E13	38.07	96.2
Nb-5E13	37.51	94.8
Nb-7E13	36.86	93.2
Nb-9E13	36.25	91.6

4.4.2 Enhancement of the critical current density Jc

In all samples, J_c reached its maximum value in the zero-field region and decreased with increasing field strength owing to vortex motion. At low fields, the irradiated films exhibited lower J_c values than the pristine film, owing to the reduced connectivity caused by the lattice-disordering agents. However, at high fields the irradiated films exhibited higher J_c values than the pristine film, thanks to the improved flux-pinning mechanism.

The double-logarithmic plot of J_c revealed the existence of two distinct regions: a low-field single-vortex-pinning region in which J_c is almost independent of the magnetic field, and an intermediate-field region exhibiting a power-law decay $J_c \approx H^{-\beta}$. The high-field J_c enhancement depends on temperature and irradiation dose, with the crossover field reaching approximately 2 T to 3 T for the film

irradiated at 7×10^{13} ion/cm² (most pronounced at 7 K, 10 K, and 15K).

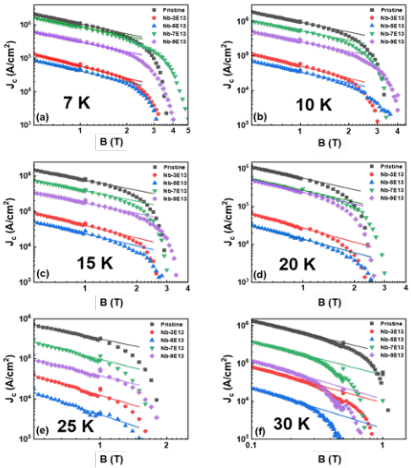


Figure 4.7. *Double logarithmic scaled field dependence of evolution of the J_c under applied magnetic field for Nb-ion irradiated MgB_2 films*

The β values at all temperatures indicate a relatively weak pinning force, with $\beta \approx 1$. Among the samples studied, Nb-7E13 exhibited the highest β value, suggesting that this sample would achieve the best J_c enhancement after Nb ion irradiation.

4.4.3 Partial shift in the flux-pinning mechanism

The dominant pinning mechanism was determined using the Dew-Hughes model. At 7 K, the pristine film yielded $p = 0.5$ and $b_{peak} = 2$, confirming a surface-pinning (2D) mechanism. Nb ion irradiation produced locally disordered lattice regions and point defects (0D). As a result, the parameter p and the peak position b shifted upward, specifically reaching $p = 0.71$ and $b_{peak} = 0.26$, and $p = 0.77$ and $b_{peak} = 0.26$, corresponding to the high irradiation doses of 7×10^{13} ion/cm²

and 9×10^{13} ion/cm², respectively. According to the Dew-Hughes model, the stronger pinning mechanism (point pinning) yields p = 1 and b_{peak} = 0.33; thus the values obtained in the samples studied indicate a partial shift of the pinning mechanism from surface pinning to point pinning, and this result accounts for the appreciable J_c enhancement at high fields.

Chapter 5. INVESTIGATION OF THE CRYSTAL STRUCTURE AND SUPERCONDUCTING PROPERTIES IN MgB_2 BY IRRADIATION OF NICKEL IONS

5.1 Simulation of the Ni-irradiation processes

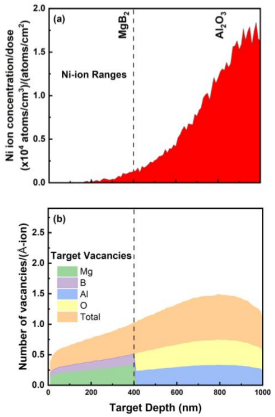


Figure 5.1. *(a) Mean projected range and (b) vacancy depth profile for 1 MeV Ni-ion irradiated MgB2 film on c-cut Al2O3 substrate.*

Simulation saves considerable cost and time in the experiments and also enables prediction of the phenomena occurring within the sample. Using the licensed SRIM software, the bombardment of the MgB_2 films (400 nm thick, density 2.57 g/cm³)

with 1 MeV Ni ions was simulated. The results showed that most of the ions stop within the substrate region, at approximately 800 nm. This indicates that most of the Ni ions pass through the film and induce lattice vibrations and point-type defects that can alter the superconducting properties.

5.2 Variations of the crystal structure in MgB_2 films before and after irradiation by Ni ions

5.2.1 XRD analysis

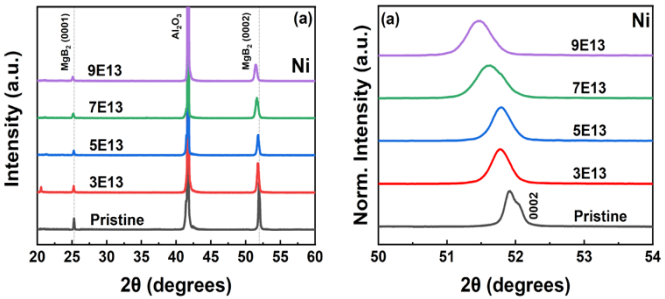


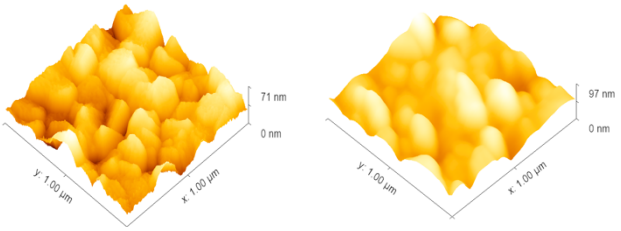
Figure 4.2. *XRD diagram of the pristine and Ni-ion irradiated MgB_2 films*

The XRD results confirmed that all MgB_2 films exhibit a preferred c-axis orientation, with 2 sharp diffraction peaks, (0001) and (0002), and that no impurity phase was detected. After Ni ion irradiation, the FWHM of the (0002) peak increased appreciably from 0.257° (pristine sample) to 0.479°, indicating a slight reduction in the crystallinity of the film. Both the (0001) and (0002) peaks tended to shift slightly toward lower 2θ values.

This shift toward lower 2θ values indicates a controlled expansion of the *c*-axis lattice parameter. Based on calculations using the hexagonal structure, the *c*-axis lattice parameter increased

progressively with increasing Ni ion dose. This expansion is driven by the nearly collinear collisions between the penetrating Ni ions and the Mg and B atoms along the *c*-axis. These defects and lattice distortions are predicted to enhance the scattering between the π and σ bands.

5.2.2 Investigation of the surface morphology before and after irradiation



(a) (b)

Figure 5.3. *AFM images: (a) pristine and (b) Ni-5E13 films*

The AFM images showed that, at a dose of 5 × 10^{13} ion/cm², Ni ion irradiation led to a marked reduction in the sharpness of the grain boundaries, reflecting partial surface amorphization together with lattice distortion. The appearance of these locally disordered regions and surface modifications is expected to act as effective pinning centers, thereby enhancing the vortex-pinning capability of the film.

5.2.3 Investigation of the crystal-lattice vibrations by Raman spectroscopy

The experimental spectra showed that, as the Ni ion dose increased, the E_{2g} peak position tended to shift toward lower values (phonon softening), reaching its lowest value at the highest dose of 9 × 10^{13} ion/cm². The ω_3 peak became increasingly dominant under irradiation. This growth indicates that the lattice distortions and strain

broke the momentum selection rules, leading to an increased contribution from the phonon density of states (PDOS); at the highest dose this peak even exceeded the E_{2g} peak position. This indicates the appearance of a large number of vacancies in the film, generating point-type defects in the crystal lattice that act as pinning centers.

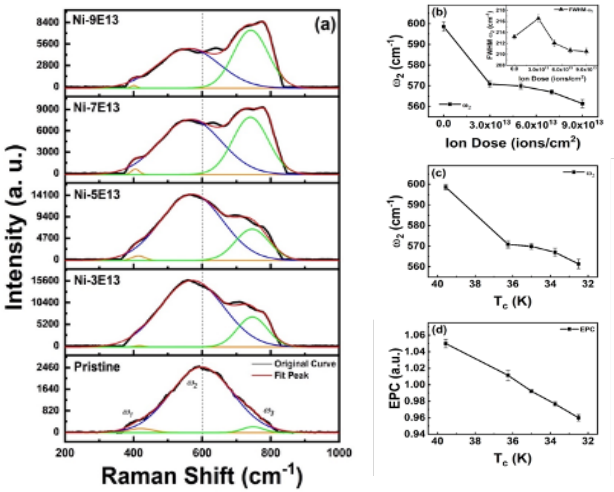


Figure 4.4. *Raman spectroscopy and parameter analysis of pristine and Ni-irradiated MgB_2 films*

The relationship between T_c, the phonon frequency, and the electron–phonon coupling constant λ was evaluated using the modified Allen-Dynes–McMillan formula:

$$T_c = (\langle\omega\rangle / 1.2) \exp\{ -1.04(1 + \lambda) / [\lambda - \mu^*(1 + 0.62\lambda)] \}$$

5.3 Superconductivity of pristine and Ni-ion irradiated MgB_2 films

5.3.1 Retention of a high critical temperature Tc

Table 5.4. *T_c values of the film before and after Ni ion irradiation*

Film	T_c (K)	T_c (Ni-ions) / T_c (pristine) (%)
Pristine	39.56	100
Ni-3E13	36.25	91.6
Ni-5E13	35.01	88.5
Ni-7E13	33.75	85.3
Ni-9E13	32.50	82.2

Increasing the Ni ion dose led to a gradual reduction of T_c and a continuous broadening of the superconducting transition region. This reduction may originate from the increased degree of disorder, the higher defect density, the weakening of intergrain coupling, and the thermal activation of vortices induced by the ion bombardment. Nevertheless, this reduction is relatively small, with T_c remaining above 30 K, which is entirely convenient for the practical application of MgB_2 superconductors.

5.3.2 Enhancement of the critical current density J_c

The irradiation drove a substantial increase in the critical current density J_c in the high-field region, most notably at the doses of 3×10^{13}, 5×10^{13}, and 7×10^{13} ion/cm². The double-logarithmic plots representing the relationship between J_c and the magnetic field reveal two distinct regions: a low-field single-vortex-pinning region (where J_c is almost independent of the magnetic field) and a high-field collective-pinning region governed by the vortices. The pinning is characterized by the value of β, calculated as in Table 5.6.

The vortex interaction follows the law $J_c \approx H^{-\beta}$. At 5 K, the exponent β decreased from 0.96 (for the pristine sample) to a minimum of 0.67 (for the highest dose), with a similar trend observed at 20 K.

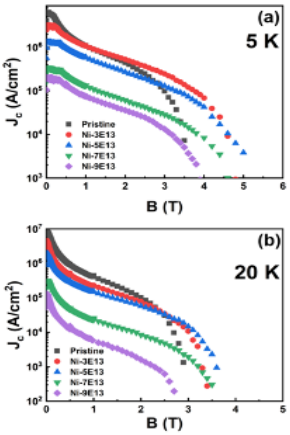


Figure 5.6. *J_c versus magnetic field of the pristine and Ni-ion irradiated MgB2 films (a) 5 K, (b) 20 K*

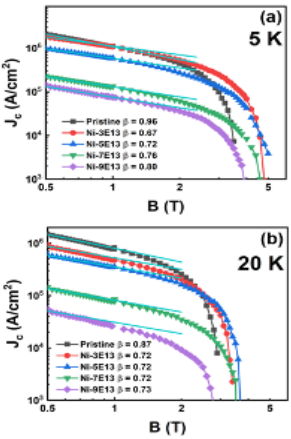


Figure 5.8. *Double logarithmic scaled field dependence of evolution of the J_c under applied magnetic field for Ni-ion irradiated MgB_2 films*

Considering the theoretical values for the weak-pinning mechanism (β = 1) and the strong-pinning mechanism (β = 0.5), the decrease of the exponent β confirms a transition from the weak-pinning mechanism to a stronger-pinning mechanism, driven by the point defects produced by the Ni ions.

Table 5.6. *Values of β before and after Ni ion irradiation*

Sample	β (5 K)	β (20 K)
Pristine	0.96	0.87
Ni-3E13	0.67	0.72
Ni-5E13	0.72	0.72

Sample	β (5 K)	β (20 K)
Ni-7E13	0.76	0.72
Ni-9E13	0.80	0.73

5.3.3 Partial shift in the flux-pinning mechanism

The pinning mechanism was evaluated using the Dew-Hughes model. For the pristine thin film, the values $p \approx 0.5$ and $b_{peak} \approx 0.2$ indicate that a normal surface-pinning (2D) mechanism at the grain boundaries is dominant, consistent with the nearly single-crystalline nature and the strong *c*-axis orientation of the film. For the high Ni ion doses (7×10^{13}, 9×10^{13} ion/cm²), the values increased appreciably to $p = 0.73$ and $b_{peak} = 0.27$, approaching the theoretical limits of the point-pinning mechanism, $p = 1$ and $q = 2$. Because the Ni ions penetrate throughout the thickness of the thin film, they produce a uniform distribution of point-type defects (including ion tracks and lattice distortion). This result leads to a partial shift from the surface-pinning to the point-pinning mechanism, and simultaneously demonstrates the coexistence of these two pinning mechanisms in the high-field region, enhancing J_c in the high-field region.

5.4 The best enhancement of J_c in MgB_2 bulks and films

Figure 5.10 re-plots the three J_c curves of the samples with the best J_c enhancement among the sample series studied: the bulk series, the Nb-irradiated film series, and the Ni-irradiated film series. It can be seen that J_c in the thin-film MgB_2 materials is considerably higher than in the bulk material. This advantage stems from the elimination of voids, the higher vacancy density after ion irradiation, and the shift in the pinning mechanism within the material.

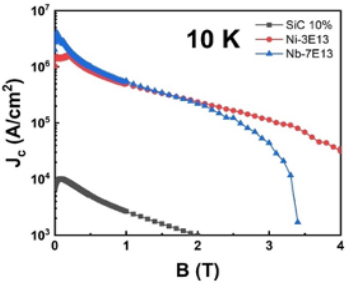


Figure 5.10. *The best enhancements of J_c in MgB_2 bulks and films at 10K*

In this study, comparing the two ion species Nb and Ni, the J_c results showed that Ni ion irradiation is more effective than Nb ion irradiation in enhancing J_c in the high-field regions. This is attributable to the magnetic nature of the Ni ions as well as their larger irradiation range, which allows the ions to penetrate the entire thin film and produce a denser and more uniform network of point defects.

CONCLUSIONS

MgB_2 has been shown to have a variety of interesting properties for power-related applications, which consists of a medium-high value of T_c ~ 39 K, the relatively high values of B_{c2} and J_c. To explore the application area, the enhancements of B_{c2} and J_c are strongly required. In this dissertation, the improvements in J_c of MgB_2 superconductors have been presented.

First, the influence of co-additions of Mg and SiC on crystal structure and superconductivity of MgB_2 bulks are studied. The pure MgB_2 and (y wt.% SiC + Mg + MgB_2) bulks were prepared using the solid-state reaction methods. The value of T_c of the MgB_2 bulks gradually decreased after the addition; however, these values remain

above 37 K, nearly the value of the pure sample (38.09 K), with the difference approximately 1 K. This is an outstanding result in maintaining T_c. Additionally, the value of B_{c2} in all of MgB_2 bulks after addition was higher than that of pure one (14.64 T). The J_c was found to increase in all the chemical added MgB_2 bulks. The pinning mechanism was found to be the normal surface pinning (with p = 0.5 and b_{peak} = 0.2) in all pure and (SiC + Mg + MgB_2) co-added bulks.

Second, the effects of Nb-ions irradiation on crystal structure and critical parameters of MgB_2 films were investigated. The pristine MgB_2 films with the average thickness of ~ 400 nm were fabricated by the HPCVD system in high quality (without impurity phases). After irradiation by Nb-ions (the energy = 1 MeV, ion beam was accelerated perpendicularly to the surface of films and the doses ranged from 3×10^{13} ions/cm^2 to 9×10^{13} ions/cm^2), the structure variations were investigated. The results not only can irradiation maintain the MgB_2 crystallinity in irradiated films, but the critical parameters also were maintained and improved. In detail, the lattice distortions lead to a slight reduction of the T_c from 39.56 K (pristine) to 36.25 K (9×10^{13} ions/cm^2), which still remains above 36 K. Meanwhile, there were enhancements of the J_c in high fields, indicated by the partial shift of the pinning mechanism from normal surface pinning to normal point pinning after irradiation. The investigation also confirmed the best enhancement of J_c achieved in the dose of 3×10^{13} ions/cm^2.

Third, the impacts of Ni-ions irradiation on crystal structure and critical parameters of MgB_2 films were investigated. With the same irradiated conditions, the degradation of the crystallinity in the Ni-ion irradiated MgB_2 films seems higher when compared to Nb-irradiated films. The obvious evidence was revealed through the

PDOS appearance in Raman spectrum, with the clearly higher peaks when the doses of irradiation rise. As a result of more structural distortions, the decrease in T_c from 39.56 K (pristine) to 32.5 K (9×10^{13} ions/cm^2) was witnessed, however still maintained above 32 K. The higher enhancements of J_c in Ni-ion irradiated MgB_2 films were revealed by comparing the value of pinning strength β, (β ~ 0.67 at 5 K, which approached the theoretical value of strong pinning β = 0.5). The finding might indicate the shift from weak to relatively strong pinning. The partial shift of the pinning mechanism from normal surface pinning to normal point pinning after irradiation proved that J_c can be enhanced in high fields. This investigation also confirmed the best enhancement of J_c achieved in the dose of 3×10^{13} ions/cm^2.

Overall, values of in-field J_c - *which are the most important results in this dissertation* - were enhanced in both MgB_2 bulks and films after addition or irradiation. The J_c in the MgB_2bulks was enhanced in the range of lower field, which possibly reflected to the fact that surface pinning was dominant in the bulk samples. Interestingly, the J_c in the Nb- and Ni-ion irradiated MgB_2 films improved in the high field, which might be attributed to the slight shift to normal point pinning. The stronger enhancement of J_c seems to be obtained in the Ni-ion irradiation, which might be explained by the higher density of the point defects in the films in the form of ion-tracks, lattice distortions.

From the main results of the dissertation, future research might expand the investigations in optimization and systematization of improving J_c in MgB_2 superconductors for practical applications.

LIST OF PUBLICATIONS

1. Duc H. Tran, **Duong T.T. Nhan*,** An T. Pham, Tien Le, Viet Cuong Le, Won Nam Kang, Dzung T. Tran, Hong Gu Lee, Jungseek Hwang, Nguyen Hoang Nam, Bui Thị Hoa, Nguyen T. Nghia, Phan Hai, Dang T.B. Hop, M. Doğruer, "Local structure, electron - phonon coupling and flux pinning properties in MgB_2 thin film using the irradiation of Nb", *Ceramics International* (2026), 52,18, 33406 - 33414.

2. Duc H. Tran, **Duong T.T. Nhan*,** An T. Pham, Nguyen Hoang Nam, Kieu Xuan Thuy, Tien Le, Viet Cuong Le, Vuong T.A. Hong, Hannoh Lee, Tuson Park, Hoo-Keong Peh, Soo-Kien Chen, M. Dogruer, "Effects of SiC and Mg co-addition on the superconducting and microhardness properties of MgB_2", *Ceramics International* (2025), 51, 19(A), 27457-27464.

3. **Duong T.T. Nhan**, An T. Pham, Tien Le, Won-Nam Kang, Dzung T. Tran, Hong-Gu Lee, Jungseek Hwang, Nguyen Hoang Nam, Ha H. Pham, Khoi M. C. Pham, Pham Ngoc Thao, Phan Hai, Soo-Kien Chen, M. Dogruer, Kieu Xuan Thuy, Duc H. Tran, "Effects of Ni irradiation on electron - phonon coupling and flux pinning in MgB_2 film via Raman spectroscopy", *J. Appl. Phys.* (2025) 138, 073901.

4. **Duong Thi Thanh Nhan**, Pham The An, Le Minh Tien, Pham Hoang Ha, Nguyen The Nghia, Nguyen Khac Man, Phan Hai, Tran Hai Duc, (2025) "Effects of Ion Irradiations on Crystal Structure and Superconducting Properties of MgB2 Films", *VNU Journal of Science: Mathematics - Physics* (2025), 41 (3), 99-106.