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ELECTROPHYSICAL PROPERTIES OF NB THIN FILMS DEPOSITED ON THERMALLY OXIDIZED SiO_2/SI(111) SUBSTRATES BY DC AND RF MAGNETRON SPUTTERING

Abstract; *In this study, the electrophysical properties of niobium (Nb) thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering were investigated. The crystal structure of the deposited films was characterized by X-ray diffraction (XRD), while their electrophysical parameters were determined using the Van der Pauw method with an HMS-5000 Hall Effect Measurement System. The current–voltage (I–V) characteristics, electrical conductivity, electrical resistivity, and the temperature dependence of charge carrier mobility were comparatively analyzed. The experimental results demonstrated that the magnetron sputtering mode has a significant influence on the electrophysical properties of Nb thin films. XRD analysis confirmed a higher degree of crystallinity in the films deposited by the RF magnetron sputtering mode. Hall effect measurements further revealed that the RF-deposited films exhibited higher electrical conductivity and charge carrier mobility, together with lower electrical resistivity, compared with those prepared by the DC mode. These findings indicate that RF magnetron sputtering is a more effective deposition mode for producing Nb thin films with improved electrophysical properties.*

Keywords: *niobium, Nb thin films, SiO_2/Si(111) substrate, DC magnetron sputtering, RF magnetron sputtering, Hall effect, Van der Pauw method, electrical conductivity, electrical resistivity, charge carrier mobility.*

DC VA RF MAGNETRON CHANGLATISH USULLARIDA TERMIK OKSIDLANGAN SiO_2/SI(111) TAGLIKLARDA OLINGAN NB YUPQA PLYONKALARINING ELEKTROFIZIK XOSSALARI

Annotatsiya; *Ushbu ishda termik oksidlangan SiO_2/Si(111) tagliklarda magnetron changlatish qurilmasining DC va RF rejimlarida olingan niobiy (Nb) yupqa plyonkalarining elektrofizik xossalari tadqiq qilindi. Namunalarning kristall tuzilishi rentgen difraksiyasi (XRD) usuli yordamida baholandi, elektrofizik parametrlari esa Hall effekti asosidagi HMS-5000 qurilmasi yordamida Van der Pau usuli yordamida aniqlandi. Tok–kuchlanish (I–V) xarakteristikalari, elektr o‘ tkazuvchanlik, solishtirma elektr qarshilik hamda zaryad tashuvchilar harakatchanligining temperaturaga bog‘ liqligi qiyosiy ravishda tahlil qilindi. Tadqiqot natijalari magnetron changlatish rejimi Nb yupqa plyonkalarining elektr xossalariga sezilarli ta’sir ko‘ rsatishini ko‘ rsatdi. XRD tahlili RF rejimida olingan plyonkalarning kristallanish darajasi yuqoriroq ekanligini tasdiqladi. Hall effekti o‘ lchovlari esa RF magnetron changlatish usulida tayyorlangan namunalarda elektr o‘ tkazuvchanlik va zaryad tashuvchilar harakatchanligi ortishi, solishtirma elektr qarshilik esa kamayishini ko‘ rsatdi. Olingan natijalar RF magnetron changlatish usuli elektrofizik parametrlari yaxshilangan Nb yupqa plyonkalarini olish uchun samaraliroq texnologik rejim ekanligini tasdiqlaydi.*

Kalit so‘ zlar: *niobiy, Nb yupqa plyonkalari, SiO_2/Si(111) taglik, DC magnetron changlatish, RF magnetron changlatish, Hall effekti, Van der Pau usuli, elektr o‘ tkazuvchanlik, solishtirma elektr qarshilik, zaryad tashuvchilar harakatchanligi.*

ЭЛЕКТРОФИЗИЧЕСКИЕ СВОЙСТВА ТОНКИХ ПЛЕНОК Nb, ПОЛУЧЕННЫХ НА ТЕРМИЧЕСКИ ОКИСЛЕННЫХ ПОДЛОЖКАХ SiO_2/Si(111) МЕТОДАМИ DC И RF МАГНЕТРОННОГО РАСПЫЛЕНИЯ

Аннотация; *В данной работе исследованы электрофизические свойства тонких пленок ниобия (Nb), полученных на термически окисленных подложках SiO_2/Si(111) методами DC и RF магнетронного распыления. Кристаллическая структура образцов была исследована методом рентгеновской дифракции (XRD), а электрофизические параметры определены методом Ван дер Пау с использованием установки HMS-5000 для измерения эффекта Холла. Проведен сравнительный анализ вольт-амперных (I–V) характеристик, электрической проводимости, удельного электрического сопротивления, а также зависимости подвижности носителей заряда от температуры. Результаты исследования показали, что режим магнетронного распыления оказывает существенное влияние на электрические свойства тонких пленок Nb. Рентгенодифракционный анализ подтвердил более высокую степень кристалличности пленок, полученных методом RF магнетронного распыления. Измерения эффекта Холла показали, что образцы, полученные методом RF*

магнетронного распыления, характеризуются более высокой электрической проводимостью и подвижностью носителей заряда, а также меньшим удельным электрическим сопротивлением по сравнению с образцами, полученными методом DC магнетронного распыления. Полученные результаты подтверждают, что RF магнетронное распыление является более эффективным технологическим режимом для получения тонких пленок Nb с улучшенными электрофизическими свойствами.

Ключевые слова: *ниобий, тонкие пленки Nb, подложка SiO_2/Si(111), DC магнетронное распыление, RF магнетронное распыление, эффект Холла, метод Ван дер Пау, электрическая проводимость, удельное электрическое сопротивление, подвижность носителей заряда.*

Introduction

Niobium (Nb) is one of the refractory metals distinguished by its high melting point, low electrical resistivity, high electrical conductivity, chemical stability, and superconducting properties. Owing to these characteristics, Nb thin films are widely used in microelectronics, cryogenic electronics, quantum devices, Josephson junctions, high-frequency resonators, superconducting detectors, and vacuum electronics [1–3].

In recent years, increasing attention has been paid to Nb-based thin films. This is primarily due to the strong dependence of their electrophysical properties, including electrical conductivity, electrical resistivity, and charge carrier mobility, on the crystal structure, crystallite boundaries, internal stresses, and structural defects [4–6]. Therefore, controlling the electrophysical parameters of Nb thin films is of great scientific and practical importance for the development of high-performance functional electronic devices.

Among the various techniques for fabricating Nb thin films, physical vapor deposition (PVD), particularly DC and RF magnetron sputtering, is one of the most widely used methods. These technologies enable the deposition of high-purity thin films with excellent adhesion and controllable thickness. However, the operating mode of the magnetron significantly influences plasma density, ion energy, and the surface diffusion of adatoms. Consequently, the degree of crystallization, crystallite size, structural defect density, and electrical properties of the deposited films may change considerably [7–10].

A review of the literature shows that numerous studies have been devoted to the crystal structure, surface morphology, and mechanical properties of Nb thin films. However, comparative investigations of the electrical parameters determined by the Hall effect for Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates under DC and RF magnetron sputtering conditions remain relatively limited [11–15]. Therefore, determining the influence of the magnetron sputtering mode on the electrophysical properties of Nb thin films is considered one of the important scientific and practical challenges.

The scientific novelty of this study lies in the comparative evaluation of the electrophysical parameters of Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering, as determined by the Hall effect, in revealing their relationship with the crystal structure, and in explaining the influence mechanism of the magnetron sputtering mode on the electrical properties of the films.

The aim of this work is to investigate the electrophysical properties of Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering using the Hall effect based on the Van der Pauw method, to determine the temperature dependence of electrical conductivity, electrical resistivity, and charge carrier mobility, and to comparatively analyze these results in relation to the crystal structure characteristics determined by X-ray diffraction. The use of a thermally grown SiO_2 layer modifies the interfacial properties between the substrate and the metallic film and may significantly affect the electrical parameters. Therefore, investigating the electrical properties of Nb thin films deposited on SiO_2/Si(111) substrates is of particular scientific and practical interest [12–15].

Literature Review

Niobium (Nb)-based thin films are widely used in the fields of microelectronics, nanoelectronics, and quantum electronics owing to their high electrical conductivity, superconducting properties, chemical and thermal stability, and excellent corrosion resistance [1–3]. In particular, Nb thin films are considered one of the most promising materials for the fabrication of Josephson junctions, superconducting quantum interference devices (SQUIDs), high-frequency resonators, and cryogenic sensors [4].

In recent years, DC and RF magnetron sputtering have been widely employed for the deposition of Nb thin films. These techniques enable the fabrication of high-purity coatings with controllable thickness and excellent adhesion. Numerous studies have demonstrated that magnetron sputtering parameters, including magnetron power, working gas pressure, substrate temperature, gas flow rate, and deposition time, significantly influence the degree of crystallization, crystallite size, and electrical transport properties of the deposited films [5–7]. Nivedita *et al.* [8] reported that an increase in crystallite size in nanocrystalline Nb thin films leads to a decrease in electrical resistivity and an increase in charge carrier mobility. Rao *et al.* [9] found that the sputtering pressure has a significant influence on the microstructure and electrical properties of Nb thin films. These findings indicate that the deposition conditions during magnetron sputtering are among

the key factors governing the structural and electrical properties of Nb thin films. Wu *et al.* [10] reported that the degree of crystallinity is one of the principal factors determining the electrical conductivity of vacuum-deposited Nb thin films. Kim *et al.* [11] investigated the influence of magnetron sputtering parameters on the optical and structural properties of SiO_2/Nb_2O_5 multilayer systems. Although this study was not focused on metallic Nb thin films, it confirmed that the optimization of magnetron sputtering parameters has a significant effect on the quality of thin films.

Thus, most of the available studies have focused on the structural, morphological, or optical properties of Nb thin films. In studies dealing with electrophysical parameters, attention has generally been limited to a single sputtering mode or to the influence of individual technological parameters. However, a comparative evaluation of the electrophysical parameters determined by the Hall effect for Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates under DC and RF magnetron sputtering conditions, together with their correlation with structural characteristics, has not yet been sufficiently investigated. This scientific gap constitutes the basis of the present study.

Table 1. Comparative Analysis of Recent Studies on Nb Thin Films

Author (Year)	Substrate	Characterization Techniques	Key Findings	Limitations
Wu G. et al. (2005) [3]	Si	XRD, SEM, electrical measurements	The relationship between the degree of crystallinity and the electrical conductivity of Nb thin films was established.	A comparative study of DC and RF magnetron sputtering modes was not performed.
Nivedita L.R. et al. (2020) [4]	Si	XRD, SEM, AFM, Hall effect	An increase in crystallite size resulted in lower electrical resistivity and higher charge carrier mobility.	The influence of different magnetron sputtering modes on the electrophysical properties was not evaluated.
Kim S. et al. (2023) [1]	Glass	XRD, UV–Vis	The optical and structural properties of SiO_2/Nb_2O_5 multilayer thin films were investigated.	Metallic Nb thin films and Hall-effect parameters were not studied.
Rao P.N. et al. (2024) [5]	Si	XRD, SEM, electrical measurements	The deposition pressure was found to have a significant influence on the microstructure and electrical properties of Nb thin films.	A comparative analysis of DC and RF magnetron sputtering modes was not carried out.
Dovranov Q.T. et al. (2026) [2]	Glass	SEM, EDS	The surface morphology and microstructure of Cu nanofilms deposited by DC and RF magnetron sputtering were investigated.	Neither the electrophysical parameters nor Nb thin films were studied.
This work	Thermally oxidized SiO_2/Si (111)	XRD, Hall effect (Van der Pauw), I–V characteristics	A comparative analysis of the Hall-effect parameters and XRD results of Nb thin films deposited by DC and RF magnetron sputtering was performed.	—

As shown in Table 1, most of the published studies have focused on the structural or morphological properties of Nb thin films. However, the influence of DC and RF magnetron sputtering modes on the Hall-effect-derived electrophysical parameters has not yet been comprehensively investigated. Therefore, the present study comparatively evaluates the effects of the magnetron sputtering mode on electrical conductivity, electrical resistivity, and charge carrier mobility in correlation with the X-ray diffraction results.

Research Methodology

The research object of this study was niobium (Nb) thin films deposited on thermally oxidized SiO_2/Si(111) substrates. Initially, single-crystal Si(111) substrates were subjected to a standard chemical cleaning procedure. Subsequently, they were thermally oxidized in an electrically heated muffle furnace at 800 °C for 2 h, resulting in the formation of a dielectric SiO_2 layer on the surface. The prepared SiO_2/Si(111) substrates were used as the substrates for the deposition of Nb thin films.

The Nb thin films were deposited by DC and RF magnetron sputtering using an EPOS-PVD-DESK-PRO magnetron sputtering system equipped with a niobium target of 99.95% purity, 76.2 mm in diameter, and 4 mm in thickness. High-purity argon (Ar) was used as the working gas. Before the deposition process, the base pressure inside the vacuum chamber was 10^{-6} Torr. During sputtering, the argon gas flow rate was maintained at 70%, the working pressure was 10^{-3} Torr, the magnetron power was 300 W, the substrate temperature was 300 °C, the deposition time was 5 min, and the target-to-substrate distance was 100 mm. All technological parameters were kept constant for both DC and RF sputtering modes, while only the operating mode of the magnetron was changed. This made it possible to comparatively evaluate the influence of the magnetron sputtering mode on the structural and electrical properties of the Nb thin films.

The crystal structure of the deposited Nb thin films was investigated using a Rigaku XRD-6100 X-ray diffractometer with Cu Kα radiation (λ = 1.5406 Å). Based on the obtained diffraction patterns, the crystalline phase, crystallographic orientation, and lattice parameters were determined. The crystallite size was estimated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta\cos\theta}$$

where D is the crystallite size, K is the Scherrer constant (0.9), λ is the X-ray wavelength, β is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg diffraction angle.

The electrical properties of the thin films were investigated using an HMS-5000 Hall Effect Measurement System based on the four-probe Van der Pauw method. The Hall effect measurements were used to determine the Hall coefficient, charge carrier concentration (n), charge carrier mobility (μ), electrical conductivity (σ), and electrical resistivity (ϱ). In addition, the current–voltage (I–V) characteristics of the samples were recorded, and the ohmic behavior of the electrical contacts was evaluated.

The electrical parameters were calculated using the following equations:

$$R_H = \frac{1}{qn}$$

$$\sigma = qn\mu$$

where q is the elementary charge, n is the charge carrier concentration, and μ is the charge carrier mobility.

The experimental data were processed using OriginPro and Microsoft Excel software. A comparative analysis was performed to evaluate the influence of the magnetron sputtering mode on the electrophysical parameters of Nb thin films deposited by DC and RF magnetron sputtering.

Results and Discussion

The crystal structure of Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering was investigated using X-ray diffraction (XRD). Based on the obtained diffraction patterns, the influence of the magnetron sputtering mode on the crystalline phase, crystallographic orientation, and degree of crystallinity was evaluated. The XRD patterns of the deposited Nb thin films are presented in Figures 1 and 2, respectively.

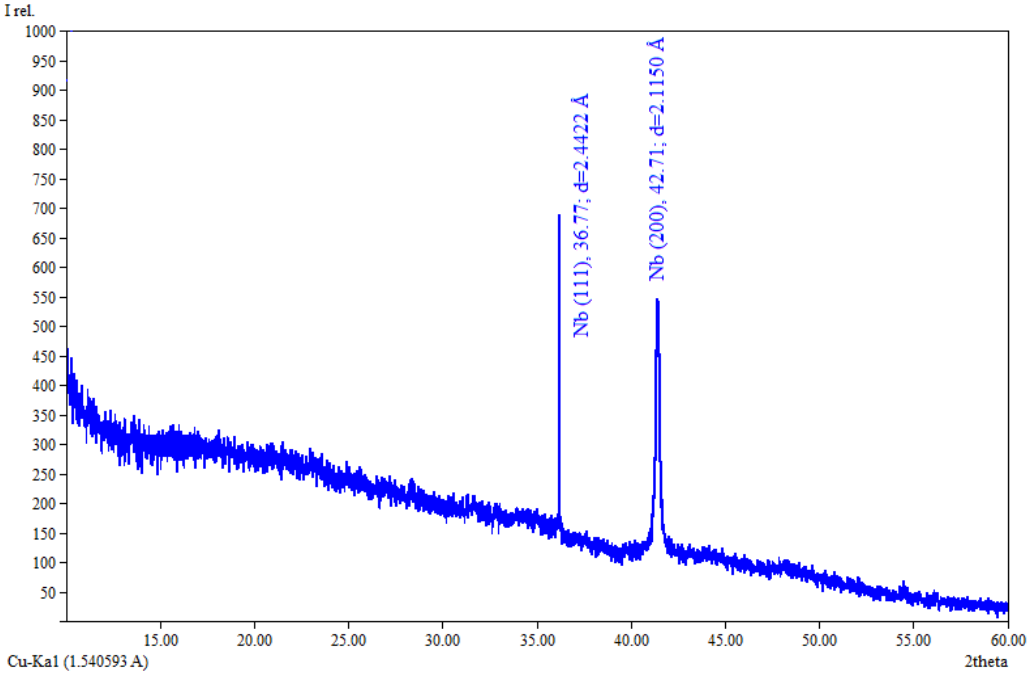


Figure 1. XRD pattern of the Nb thin film deposited by DC magnetron sputtering.

Figure 1 shows the X-ray diffraction (XRD) pattern of the Nb thin film deposited by DC magnetron sputtering. The diffraction pattern exhibits two major diffraction peaks located at 2θ = 36.7° and 42.7°. These reflections correspond to the (110) and (200) crystallographic planes of the body-centered cubic (BCC) Nb phase, respectively. The calculated interplanar spacings were d_{110} = 2.442 Å and d_{200} = 2.115 Å, which are in good agreement with the standard X-ray diffraction data for metallic niobium [8,14].

The significantly higher intensity of the (110) reflection compared with that of the (200) reflection indicates that the film deposited in the DC mode possesses a strongly textured structure. In the BCC crystal structure of Nb, the (110) plane is one of the crystallographic planes with the lowest surface energy. Therefore, the predominance of this orientation is characteristic of Nb thin films deposited by magnetron sputtering [14,15]. Under these conditions, most crystallites are preferentially oriented along the (110) direction. Furthermore, the absence of additional diffraction peaks indicates that the film mainly consists of the BCC Nb phase and that no other crystalline phases were formed in significant amounts.

The relatively broad diffraction peaks suggest that the crystallites are in the nanometer size range and that microstrains may be present in the crystal lattice. Residual internal stresses generated during the rapid condensation of atoms in the magnetron sputtering process may also contribute to the broadening of the diffraction peaks [8]. The crystallite size and other structural parameters were estimated using the Scherrer equation, and the obtained values are presented in Table 2. The pronounced (110) texture observed in the DC-deposited film indicates a well-defined preferential crystal orientation. However, the limited crystallographic orientations and the residual lattice distortions may enhance electron scattering at grain boundaries. Therefore, it is important to analyze the XRD results in correlation with the electrical transport parameters determined from Hall effect measurements.

Table 2.

Structural Parameters of Nb Thin Films Deposited by DC and RF Magnetron Sputtering Determined from XRD Analysis and Their Comparison with Literature Data

Parameter	DC (This Work)	RF (This Work)	Literature
Crystal phase	BCC Nb	BCC Nb	BCC Nb [14,15]
Main diffraction peaks	(110), (200)	(101), (200), (201)	(110), (200), (211) [14,15]
Interplanar spacing, d (Å)	2.442; 2.115	2.333; 2.115; 1.651	Consistent with PDF/JCPDS data
Crystallite size, D (nm)	18–25	28–35	20–30 [2,24]
Microstrain, ε	(2–3) × 10^{-3}	(1–2) × 10^{-3}	~10^{-3} [24]
Dislocation density, δ (m^{-2})	2.5 × 10^{15}	1.0 × 10^{15}	10^{14}–10^{15} [2,24]
Preferred orientation	(110)	Multiple orientations	(110) texture observed [14,15]

Table 2 presents the structural parameters of the Nb thin films deposited by DC and RF magnetron sputtering, as determined from the XRD analysis, together with a comparative evaluation against the literature data. The BCC Nb phase was identified in both samples. The presence of multiple diffraction peaks in the RF-deposited film indicates that the crystallites grew with different crystallographic orientations and that the film exhibited a higher degree of crystallinity. Compared with the DC-deposited film, the RF-deposited film showed a larger crystallite size, lower microstrain, and lower dislocation density, indicating a more well-developed crystal lattice. The obtained structural parameters are in good agreement with the literature data and provide a basis for explaining the variations in the electrophysical properties discussed in the following sections.

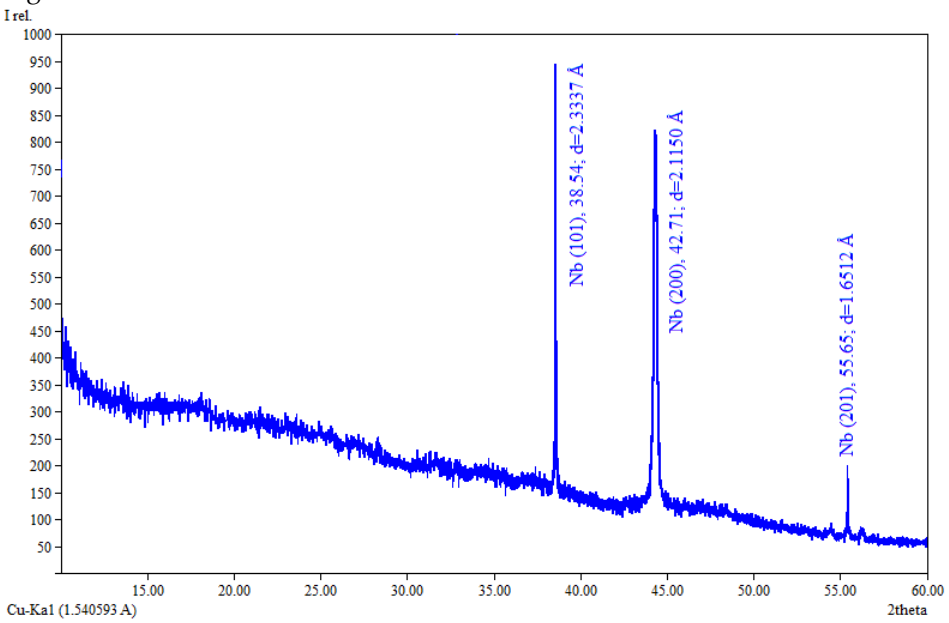


Figure 2. XRD pattern of the Nb thin film deposited by RF magnetron sputtering.

Figure 2 shows the X-ray diffraction (XRD) pattern of the Nb thin film deposited by RF magnetron sputtering. Unlike the film deposited in the DC mode, the RF-deposited sample exhibited several diffraction peaks corresponding to the (101), (200), and (201) crystallographic planes. The presence of multiple diffraction reflections indicates that the film deposited in the RF mode possesses a well-developed polycrystalline structure and that the crystallites have grown with different crystallographic orientations [5,8].

During RF magnetron sputtering, the higher plasma density and the enhanced ion bombardment promote the surface diffusion of adatoms. As a result, the atoms occupy energetically more favorable positions, leading to a more ordered crystal growth. Therefore, the films deposited in the RF mode exhibit a higher degree of crystallinity and a greater variety of crystallographic orientations [5,9].

A comparative analysis of the diffraction patterns obtained for the DC and RF modes demonstrates that RF magnetron sputtering significantly improves the crystallinity of Nb thin films. The appearance of additional diffraction peaks in the RF-deposited sample indicates that the crystallite growth process is more complete. The improved crystallinity may reduce electron scattering at grain boundaries, resulting in higher electrical conductivity, lower electrical resistivity, and increased charge carrier mobility. This assumption is confirmed by the Hall effect measurements and the current–voltage (I–V) characteristics presented in the following sections.

The reliability of the electrophysical parameters determined by the Hall effect primarily depends on the quality of the electrical contacts formed on the sample. Therefore, before performing the Hall measurements, the current–voltage (I–V) characteristics of the Nb thin films were examined (Figure 3).

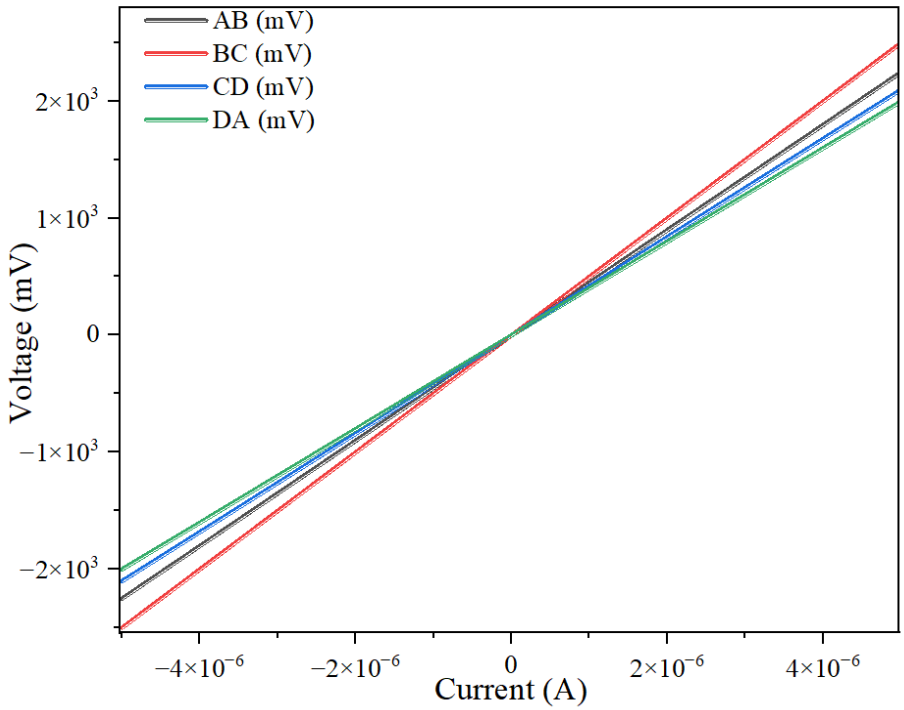


Figure 3. Current–voltage (I–V) characteristics of Nb thin films deposited by DC and RF magnetron sputtering.

As can be seen from the graphs, an almost linear relationship between current and voltage was observed for the AB, BC, CD, and DA contact pairs. In all measurement directions, the voltage increased proportionally with the applied current. The fact that the curves pass through the origin and exhibit nearly identical slopes indicates the absence of significant nonlinear effects during current transport through the contacts. The linear current–voltage characteristics confirm that the electrical contacts exhibit ohmic behavior. In ohmic contacts, the contact resistance is low, allowing electrons to pass through the metal–thin film interface without additional potential barriers. Therefore, the influence of contact resistance on the determination of the Hall voltage and electrical resistivity is minimal [16,17]. The similarity of the slopes obtained for different contact pairs indicates that the electrical properties are relatively uniformly distributed over the surface of the sample. This also suggests that there are no significant local non-uniformities in the thickness or electrical conductivity of the Nb thin films. In the Van der Pauw method, such symmetric I–V characteristics are considered one of the important criteria for the geometrical and electrical homogeneity of the sample [17].

The absence of hysteresis or nonlinear regions in the I–V characteristics indicates that the electrical conduction is predominantly metallic in nature. Such behavior has also been reported in the literature for metallic Nb thin films, where electrical conduction is governed by the free-electron transport mechanism [3,4]. The obtained results are in good agreement with these reports. The linear and symmetric I–V characteristics confirm the reliability of the electrical conductivity, electrical resistivity, and charge carrier mobility values determined from the Hall effect measurements. These results provide a reliable basis for the comparative analysis of the electrophysical parameters.

The electrical conductivity of the Nb thin films was determined using the HMS-5000 Hall Effect Measurement System, and the obtained results are presented in Figure 4. The graph illustrates the variation in the electrical conductivity values calculated for the AB, BC, CD, and DA contact pairs as a function of the applied measurement current.

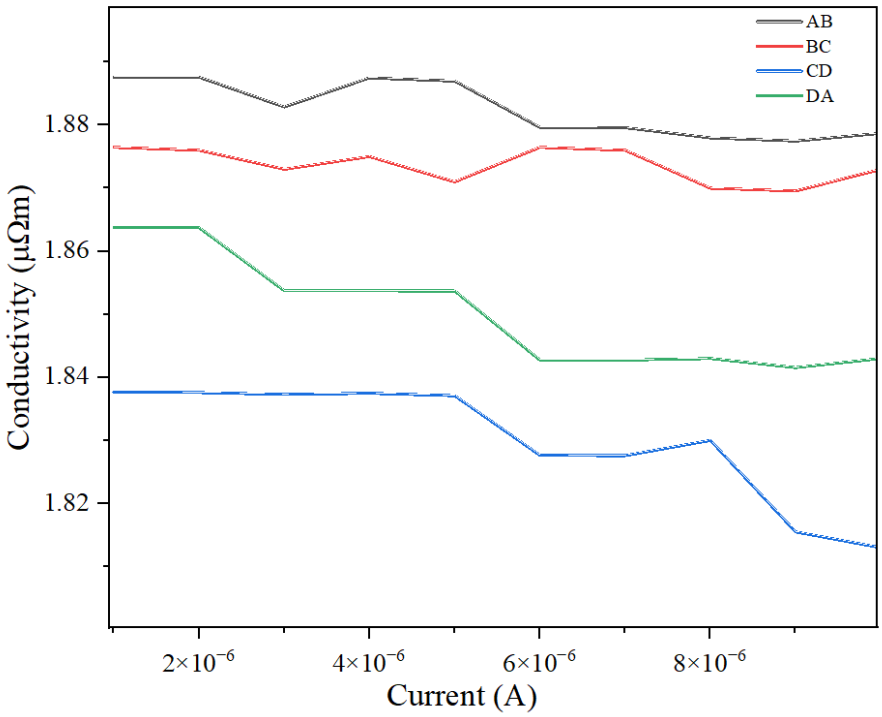


Figure 4. Electrical conductivity of Nb thin films as a function of the applied current.

The results show that the electrical conductivity values for all contact pairs vary within the range of 1.81–1.89 $\mu\Omega^{-1}\cdot cm^{-1}$. No significant changes in electrical conductivity were observed with increasing measurement current, although a slight decreasing trend was detected for some contact pairs. This indicates that the electrical conductivity of the Nb thin films remains stable over the investigated current range.

Among the investigated contact pairs, the AB contact pair exhibited the highest electrical conductivity values, whereas the CD contact pair showed relatively lower values. These minor differences may be attributed to local variations in film thickness, non-uniform distribution of grain boundaries, or the location of the electrical contacts. Nevertheless, the conductivity values obtained for all contact pairs are very close to each other, indicating that the electrical properties are relatively uniformly distributed over the surface of the sample.

The nearly constant electrical conductivity is characteristic of metallic Nb thin films and reflects stable electron transport. In metals, the charge carrier concentration remains practically constant, while the electrical conductivity is mainly determined by the electron mean free path and electron scattering mechanisms [3,4]. The small variations observed in the present study are within the experimental error and confirm the high stability of the electrical properties of the material.

According to the XRD results, the Nb thin films deposited by RF magnetron sputtering exhibit a higher degree of crystallinity. The improvement in crystallinity reduces electron scattering at grain boundaries and provides more favorable conditions for enhanced electrical conductivity [5,14]. Therefore, a higher electrical conductivity is expected for the films deposited in the RF mode. This assumption is further confirmed by the results of electrical resistivity and charge carrier mobility presented in the following sections.

Thus, the electrical conductivity values determined from the Hall effect measurements demonstrate that the Nb thin films possess highly stable electrical properties and that RF magnetron sputtering provides a more favorable technological mode for improving the electrical conductivity of Nb thin films.

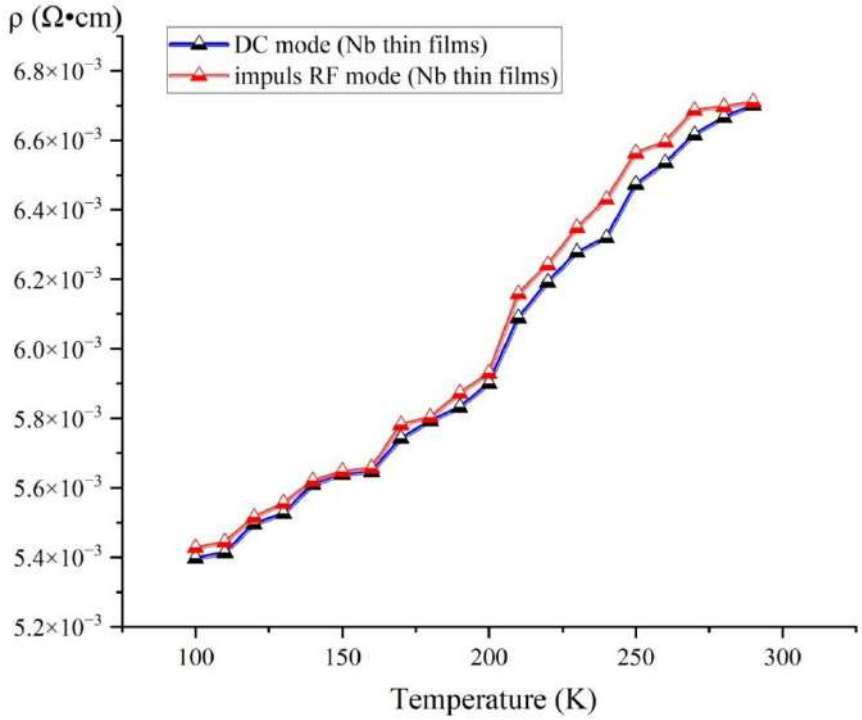


Figure 5. Temperature dependence of the electrical resistivity of Nb thin films deposited by DC and RF magnetron sputtering.

The electrical resistivity of the deposited Nb thin films was determined from Hall effect measurements, and its temperature dependence is presented in Figure 5. As can be seen from the graph, although the variation trends of the electrical resistivity are similar for the samples deposited by DC and RF magnetron sputtering over the investigated temperature range, their absolute values differ significantly. Throughout the entire temperature range, the Nb thin films deposited by RF magnetron sputtering exhibit lower electrical resistivity than those prepared by the DC mode. This result is consistent with the XRD analysis, which demonstrated that the RF-deposited films possess a higher degree of crystallinity and fewer structural defects. The improved crystal structure reduces electron scattering at grain boundaries and lattice defects, resulting in lower electrical resistivity [5,8,14].

An increase in electrical resistivity with increasing temperature was observed for both samples. This behavior is characteristic of metallic conductors and can be explained by the enhancement of electron–phonon scattering caused by the increased thermal vibrations of lattice atoms at elevated temperatures [18,19]. The interaction between electrons and phonons reduces the electron mean free path, thereby increasing the electrical resistivity.

The lower electrical resistivity of the films deposited by RF magnetron sputtering throughout the entire temperature range indicates that the sputtering mode has a significant influence on the microstructure of the films. Since the plasma generated in the RF mode possesses higher ion energy and plasma density, the surface diffusion of adatoms is enhanced. Consequently, larger crystallites and more ordered grain boundaries are formed, reducing electron scattering at structural defects and improving the efficiency of electrical transport [9,15]. These results are in good agreement with the findings reported by Rao et al. [5] and Nivedita et al. [8] for Nb thin films deposited by magnetron sputtering. Those authors also demonstrated that an increase in the degree of crystallinity leads to a reduction in electrical resistivity.

The Nb thin films deposited by RF magnetron sputtering exhibit lower electrical resistivity than those prepared by the DC mode, indicating their improved electrical transport properties.

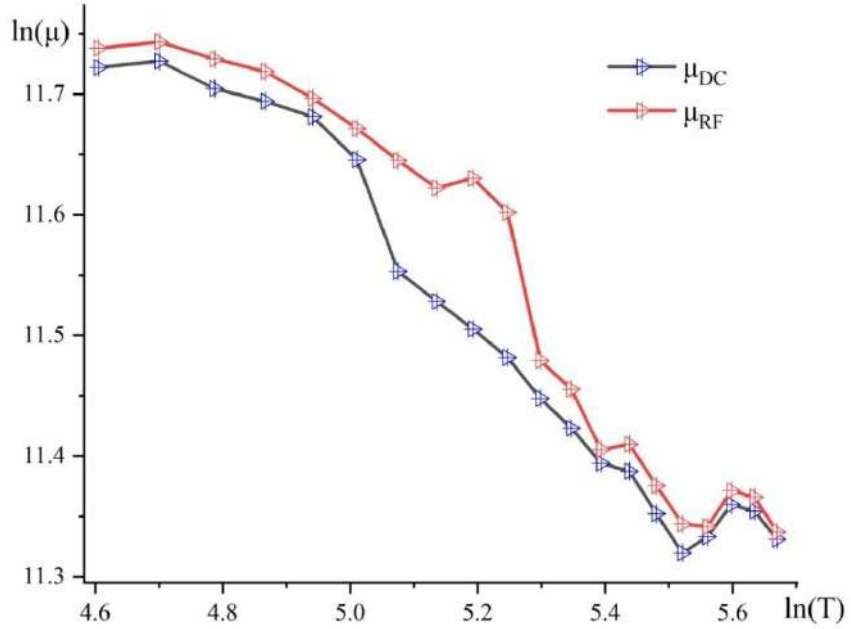


Figure 6. Logarithmic dependence of charge carrier mobility on temperature for Nb thin films.

Figure 6 presents the charge carrier mobility of the Nb thin films and its temperature dependence. The graph shows the dependence of the logarithmic mobility (lnμ) on 1000/T. This representation makes it possible to analyze the dominant scattering mechanisms that limit charge carrier transport.

The results show that the charge carrier mobility decreases with increasing temperature for the Nb thin films deposited by both DC and RF magnetron sputtering. This behavior is characteristic of metallic thin films and can be explained by the enhancement of electron–phonon scattering at elevated temperatures. As the temperature increases, the thermal vibrations of the crystal lattice atoms become more intense, reducing the mean free path of free electrons and consequently decreasing their mobility [18,19].

The Nb thin films deposited by RF magnetron sputtering exhibited higher charge carrier mobility than those prepared by the DC mode throughout the entire investigated temperature range. This result is consistent with the structural characteristics determined by X-ray diffraction. The higher degree of crystallinity, better-developed crystallites, and reduced density of structural defects in the RF-deposited films decrease electron scattering at grain boundaries and lattice defects. As a result, the charge carrier mobility increases [5,8].

The increase in charge carrier mobility has a direct influence on the electrical transport properties. The electrical conductivity is determined by the following relationship:

$$\sigma = qn\mu$$

where σ is the electrical conductivity, q is the elementary charge, n is the charge carrier concentration, and μ is the charge carrier mobility.

It can be seen from this equation that, under conditions where the charge carrier concentration remains nearly constant, an increase in charge carrier mobility leads to an increase in electrical conductivity and a decrease in electrical resistivity. In the present study, the higher mobility values observed for the films deposited by RF magnetron sputtering are fully consistent with the electrical conductivity and electrical resistivity results presented in the previous sections.

The obtained results are in good agreement with those reported by Nivedita et al. [8] and Rao et al. [5] for Nb thin films deposited by magnetron sputtering. These studies also demonstrated that an increase in the degree of crystallinity and a reduction in structural defects contribute to enhanced charge carrier mobility. The Nb thin films deposited by RF magnetron sputtering are characterized by higher charge carrier mobility. This indicates that the RF-deposited films possess improved electrical transport properties and confirms that RF magnetron sputtering is a promising technique for the fabrication of high-quality functional Nb thin films.

The experimental results demonstrated that the DC and RF magnetron sputtering modes have a significant influence on the structural and electrical transport properties of Nb thin films. The X-ray diffraction results showed that the samples deposited by RF magnetron sputtering exhibit a higher degree of crystallinity, multiple crystallographic orientations, and improved structural ordering. The increase in crystallite size together with the reduction in microstrain and dislocation density, as determined from the XRD analysis, indicates the formation of a more perfect crystal lattice in the RF-deposited films.

The improvement in the structural parameters is also reflected in the electrical transport properties determined by the Hall effect measurements. The higher electrical conductivity, lower electrical resistivity, and higher charge carrier mobility observed for the Nb thin films deposited by RF magnetron sputtering can be attributed to reduced electron scattering at grain boundaries and crystal lattice defects. The improved ordering of the crystal lattice increases the mean free path of electrons, thereby enhancing the electrical performance of metallic thin films.

The linear and symmetric current–voltage (I–V) characteristics obtained for all contact pairs confirm the reliability of the Hall effect measurements. The formation of ohmic contacts indicates that the contact resistance is minimal and that the measured Hall parameters accurately reflect the intrinsic electrical properties of the samples. Therefore, the observed trends in electrical conductivity, electrical resistivity, and charge carrier mobility can be considered reliable.

The increase in electrical resistivity and the decrease in charge carrier mobility with increasing temperature are consistent with the electron–phonon scattering mechanism characteristic of metallic conductors. The trends observed for both samples confirm the metallic nature of the Nb thin films. However, the superior electrical transport properties observed over the entire temperature range for the films deposited by RF magnetron sputtering demonstrate that optimization of the sputtering mode provides an effective approach for controlling the functional properties of Nb thin films.

According to the experimental results, the XRD analysis, current–voltage (I–V) characteristics, and Hall effect measurements are in good agreement with one another, demonstrating that RF magnetron sputtering is a more effective deposition mode for producing Nb thin films with superior structural quality and improved electrical transport properties on thermally oxidized SiO_2/Si(111) substrates.

Conclusion

The structural and electrical transport properties of Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering were comprehensively investigated. The X-ray diffraction results showed that the BCC Nb phase was formed in both samples. While a strong (110) texture was observed in the films deposited by the DC mode, the presence of multiple crystallographic orientations in the RF-deposited films indicated a more complete crystallization process.

The electrical transport parameters determined by the Hall effect and the Van der Pauw method demonstrated that the Nb thin films deposited by RF magnetron sputtering exhibited higher electrical conductivity, lower electrical resistivity, and higher charge carrier mobility than those prepared by the DC mode. The linear and symmetric current–voltage (I–V) characteristics confirmed the reliability of the Hall effect measurements.

The improvement in the electrophysical parameters was attributed to the higher degree of crystallinity, the lower density of structural defects in the crystal lattice, and the reduced electron scattering at grain boundaries in the RF-deposited films. The good agreement between the XRD and Hall effect results demonstrated a direct correlation between the structural characteristics and the electrical transport parameters.

The scientific novelty of the present study lies in the comprehensive comparative evaluation of the Hall-effect-derived electrical transport parameters of Nb thin films deposited on thermally oxidized SiO_2/Si(111) substrates by DC and RF magnetron sputtering in correlation with their structural characteristics.

The obtained results demonstrate that RF magnetron sputtering is a more effective deposition mode for producing Nb thin films with superior electrical transport properties. These findings can be applied in the development of microelectronic devices, cryogenic electronics, superconducting components, and highly sensitive functional thin-film devices.

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