Review Article

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# Niobium in electrochemical technologies: advancing sensing and battery applications

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**Abstract:** Niobium, a versatile transition metal, plays a vital role in expanding electrochemical technologies due to its unique combination of physical and chemical properties, such as high stability, conductivity, and compatibility with varied materials. This review delves deeply into the applications of niobium in electrochemical sensing and energy storage systems, focusing on its transformational potential. It begins by explaining the fundamental features of niobium that make it an excellent material for these applications. The principles of electrochemical sensors are elaborated, with a focus on their significance in areas such as healthcare diagnostics, environmental monitoring, and industrial processes. The review highlights the fabrication techniques for niobium-based sensors, detailing advancements in sensitivity and specificity achieved through niobium compounds. In the domain of energy storage, the review examines niobium's integration into lithium-ion, sodium-ion, and lithium-sulfur batteries. It discusses how niobium compounds enhance battery performance, including improvements in energy density, cycling stability, and charge-discharge efficiency. Comparative analyses with conventional materials are presented to underscore the superior functionality of niobium-based systems. By synthesizing current research, the review identifies critical knowledge gaps and potential areas for future investigation, ultimately underscoring niobium's pivotal role in driving innovation in electrochemical technologies.

**Keywords:** niobium; electrochemical sensors; lithium ion battery; sodium ion battery; lithium sulfur battery

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## 1 Introduction

Niobium (Nb) is the element 41 on the periodic table. It was originally known as columbium (Cb). Imagine it as a light grey metal with a very malleable crystalline structure. Niobium can be stretched out like iron and has a hardness comparable to pure titanium when it's all by itself.[1] Since niobium reacts slowly with oxygen in the environment, it is a popular hypoallergenic substitute for nickel in jewelry. You'll often spot it in minerals like pyrochlore and columbite, which is why folks used to call it "columbium".[2,3] Niobium derives its name from Greek mythology, specifically Niobe, the daughter of Tantalus, from whom tantalum gets its name. This terminology reflects the striking similarity between the two elements in both physical and chemical properties, often making it challenging to differentiate.[2,4–6]

In 1801, English chemist Charles Hatchett identified a new element resembling tantalum and named it columbium. However, in 1809, another English chemist, William Hyde Wollaston, mistakenly believed that tantalum and columbium were the same element.[7,8] In 1846, German chemist Heinrich Rose discovered a second element within tantalum ores, which he named niobium. Subsequent scientific investigations in 1864 and 1865 established that niobium and columbium were indeed the same elements, distinct from tantalum. For about a century, both names were used interchangeably. Niobium was formally recognized in metallurgy in the United States.[9]

Niobium didn't see commercial use until the early 20th century. It became a crucial component in high-strength, low-alloy steels. Brazil stands as the primary producer of niobium and ferroniobium, an alloy comprising 60–70 % niobium mixed with iron.[10] Niobium finds its primary application in alloys, with a significant portion used in special steel, particularly for gas pipelines. Even though these alloys typically contain just a small fraction, up to 0.1 %, of niobium, they greatly improves the steel's strength by removing carbide and nitride. The temperature resilience of niobium-infused superalloys is crucial for their utilization in jet and rocket engines.[11,12]

Niobium plays a vital role in various superconducting materials, often alongside titanium and tin, commonly found in the superconducting magnets of MRI scanners. Beyond this, niobium finds applications in welding, nuclear industries, electronics, optics, numismatics, and jewelry. In the latter two fields, its low toxicity and the iridescent effects achieved through anodization are highly valued properties. Given its indispensable role in technology, niobium is deemed a technology-critical element.[13,14] In 1864, De Marignac became the first to produce niobium metal. He achieved this by heating niobium chloride in a hydrogen atmosphere, leading to its reduction.[15] While de Marignac successfully produced tantalum-free niobium on a larger scale by 1866, it wasn't until the early 20th century that niobium found its way into incandescent lamp filaments, marking its first commercial application.[16] The use of niobium in incandescent lamp filaments was short-lived as tungsten, with its higher melting point, quickly replaced it. However, in the 1920s, the discovery that niobium enhances the strength of steel emerged, and since then, this application has remained its primary use.[17] In 1961, Eugene Kunzler, an American physicist, and his colleagues at Bell Labs made a groundbreaking discovery: they found that niobium-tin retains its superconductivity even in the presence of strong electric currents and magnetic fields. This marked the first material capable of supporting the high currents and fields required for practical high-power magnets and electrical machinery. This pivotal discovery laid the groundwork for the production of long multi-strand cables wound into coils, enabling the creation of large, powerful electromagnets. These electromagnets have since been used in various applications, including rotating machinery, particle accelerators, and particle detectors, revolutionizing these fields.[18,19]

## 2 Physical and chemical properties of Nb

Niobium (as shown in Figure 1) is a transition metal with atomic number 41 and an atomic mass of 92.906 g/mol, exhibit a silvery-gray appearance with a density of 8.57 g/cm$^3$. At room temperature, it exists as a solid, with a melting point of 2,468 degrees Celsius and a boiling point of 4,927 degrees Celsius. In terms of chemical properties, niobium is relatively inert under normal conditions, but can react with oxygen at high temperatures to form niobium oxide ($Nb_2O_5$). It displays multiple oxidation states, including $^{+}2$, $^{+}3$, $^{+}4$, and $^{+}5$, and forms various compounds like niobium carbide (NbC) and niobium nitride (NbN).[5,20] Renowned for its resistance to corrosion, niobium finds utility in environments where exposure to harsh conditions is frequent. Additionally, its high electrical conductivity makes it advantageous in electronic and electrical applications. Niobium's strong affinity for oxygen facilitates the formation of stable oxides, contributing to its corrosion resistance. Furthermore, it forms alloys with other metals, such as steel, which enhances their mechanical and chemical properties.[21]

## 3 Overview of electrochemical sensors and their importance

Electrodes are utilized as transducer elements in a type of instrument called an electrochemical sensor. In many fields today, including monitoring, metal processing, hazardous ecological, environmental analyses in manufacturing, plant treatment, medical, biotechnological, quantitative analysis sensors, and natural product applications, electrochemical sensors are becoming increasingly important.[23–26] Electrochemical sensors provide reliable and repeatable data for linear responses and specific chemical species using analytical signals and devices.[27] Commonly utilized electroanalytical sensor types include conductometric, potentiometric, and amperometric sensors. Due to its ability to transform biological reactions into electrical signals, biosensors are also regarded as essential instruments in several scientific applications for the detection and measurement of numerous biochemical processes. The use of electrochemical sensors for the identification of hazardous, radioactive, and carcinogenic chemicals as well as toxic biomolecules has recently advanced, demonstrating the value of these sensors in environmental research.[28]

## 4 Electrochemical sensors principles

Electrochemical sensors use a chemical reaction to measure the concentration of a specific gas in an environment, as

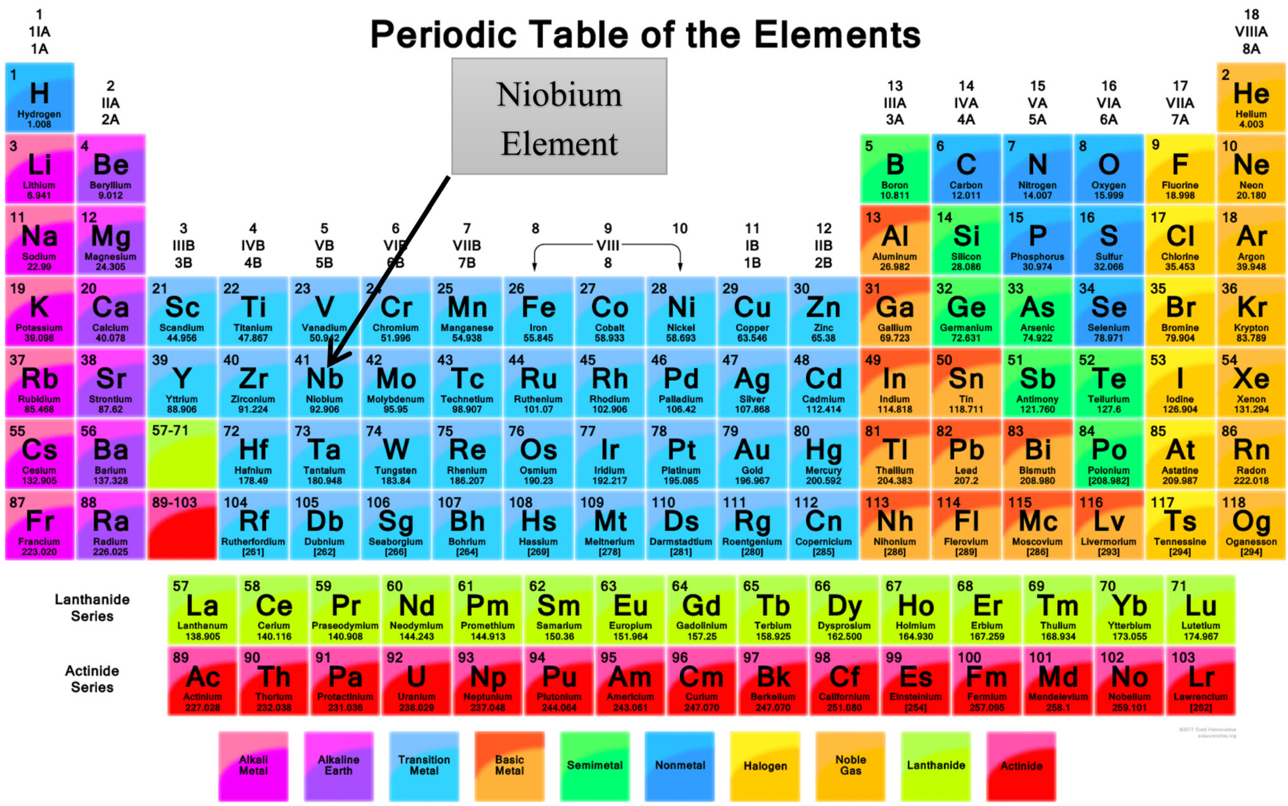


**Figure 1:** Position of niobium (Nb) on the periodic table; niobium is located in group 5 (formerly group VB) of the transition metals, situated in period 5; it is positioned below vanadium (V) and above tantalum (Ta), highlighting its classification within a group known for versatile chemical and physical properties.[22]

shown in Figure 2. There are many different applications for electrochemical sensors, and they continue to play an important role in many industries.[29] Electrochemical sensor technology has been used in industry for many years. The current requirements for small sensors with low energy consumption and ease of use have enabled the continuous development of the technology. Electrochemical sensors can be constructed differently depending on the application and, therefore, provide tailored solutions to new emerging applications.[30] Electrochemical sensors work by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration. Consisting of two electrodes (a working electrode and a counter electrode), the sensor operates by allowing charged molecules to pass through a thin layer of electrolyte.[31,32]

## 5 Importance of electrochemical sensors in various fields

Due to their long-term reliability, high sensitivity, accuracy, affordability, speed, and ease of miniaturization, electrochemical sensors have long been utilized for studying biological, environmental, industrial, and pharmaceutical species. For over 20 years, a variety of unique nanomaterials have been included in electrochemical tests to enhance analytical performance. These include metals, conductive polymers, metal oxides, and metal-organic and carbon-based nanomaterial frameworks.[34–36] Through the use of recognition molecules like enzymes, antibodies, and aptamers, as well as bioinspired receptors that can

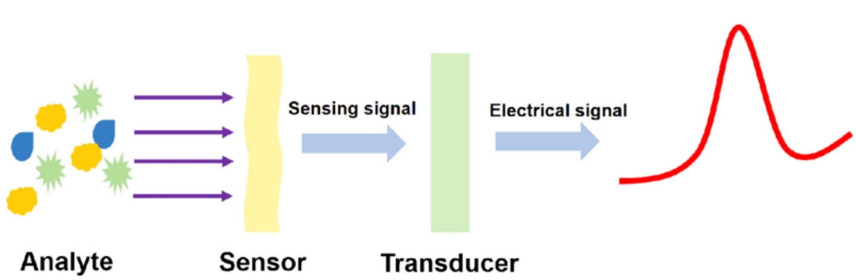


**Figure 2:** Structure and basic principle of electrochemical sensors.[33]

precisely and efficiently capture targets, these modifications enhance the loading capacity and, consequently, the specificity of electrochemical sensors.[37] Strong electrocatalytic activity for specific electrochemical processes is intimately connected to this goal. Furthermore, it is feasible to increase surface area and electrical conductivity by changing the form and structure of the surface, which should improve the sensitivity of these tests. Due to novel applications, including wearables, point-of-care diagnostics, *in vivo* analysis, and single-molecule sensing, electrochemical sensors have become more and more popular recently.[38]

Electrochemical sensors offer numerous advantages, including high sensitivity (allowing low LODs and LOQs), fast analytical response (ideal for flow analysis and alert systems), and simplicity (enabling diverse electrode materials, geometries, and configurations). Additionally, their low cost and adaptability enhance their utility across various analytical systems.[39,40]

## 6 Characteristics of niobium-based sensors: fabrication of different sensors of NB

Niobium-based sensors offer several characteristics that make them attractive for various electrochemical sensing applications. Here are some key characteristics:

**Chemical Stability:** Niobium has great chemical stability, making it appropriate for usage in hostile conditions and interaction with a wide range of chemicals without experiencing significant deterioration.[41]

**Biocompatibility:** Consider niobium a useful metal in the medical and technological fields. It gets along nicely with biological systems, like a good friend who fits in seamlessly at any social gathering. This makes it great for things like biosensors and medical devices where it needs to communicate easily with biological samples, similar to a friend who understands how to handle any social scenario with ease.[42]

**Wide Potential Window:** Niobium is like a large playground for electrochemical measurements. It provides ample area for a variety of tests without interfering with their reactions. This is critical for achieving highly precise and specific results in electrochemical sensing. So, it's like having a clean slate to work with, ensuring that your trials hit the mark without any distractions.[43]

**High Conductivity:** Consider niobium to be the fastest messenger in the field of sensors. Because of its great electrical conductivity, it is extremely effective at transmitting messages (electrons) between the sensor's surface and the molecules under analysis. This speedy interchange enables niobium-based sensors to react quickly and take up even the smallest signals. So, you can rely on niobium to be like the sprinter of the sensor world, ensuring quick and accurate detection.[44]

**Large Surface Area:** Consider niobium-based materials to be plenty of nooks and crannies for analytes to hang around in. This turns them into a magnet for molecules, increasing the sensor's sensitivity. It's similar to having a larger net to catch more fish: more surface area implies more areas for molecules to attach to, ensuring that the sensor doesn't miss anything.[45]

**Compatibility with Nanotechnology:** Niobium can be integrated into nanomaterials and nanostructures, opening up opportunities for the development of miniaturized and highly sensitive sensors with enhanced performance.[46]

**Environmental Friendliness**: Niobium really shows off its flexibility when it teams up with nanotechnology. Together, they create sensors that are not only tiny but also super sensitive. It's like going from a clunky old device to a sleek, high-tech gadget. Thanks to niobium's collaboration with nanotech, we get sensors that deliver a big punch in a small size.[47]

## 7 Fabrication of Nb sensor

(1) **Deposition:** To kick off making an Nb sensor, the first move is laying down a thin layer of niobium on a good base, like silicon dioxide or sapphire. You can pull this off using methods like sputtering or molecular beam epitaxy.[48]
(2) **Patterning:** After getting the Nb film in place, it's time to shape it up using photolithography or electron beam lithography. These techniques help define where the sensor's sensing area and contacts will be.[49]
(3) **Integration:** Once the sensor is ready, it's all about teaming it up with readout electronics and maybe some other components, depending on what it's being used for. This integration guarantees the sensor's ability to perform its function, be it temperature monitoring, gas detection, or something else completely.[50]
(4) **Characterization:** It is now time to test the sensor once it has been assembled. This entails putting it through testing and analysis to determine its sensitivity, detection limit, linear response, and other critical performance metrics. By doing this step, you can make sure that the sensor is in good working order and prepared to take on any responsibilities you assign it.[51]

**Table 1:** Comparison of the detection limits and linearity ranges of different types of Nb sensors based on available references, depending on the specific application and requirements, one can choose the appropriate type of Nb sensor.

| Sensor type | Detection limit | Linearity range | Reference |
|---|---|---|---|
| SQUIDs | Femtotesla levels | Wide dynamic range | 57 |
| Nanobridge josephson junctions | Picowatt range | Dependent on application | 58 |
| Nanomechanical resonators | Attogram range | Dependent on application | 59 |
| Superconducting TES | Sub-electron volt range | Dependent on application | 55 |
| Nanowire sensors | Single-photon or single-electron regime | Dependent on application | 60 |

# 8 Types of Nb sensors

**Superconducting Quantum Interference Devices (SQUIDs):** Highly sensitive magnetic field sensors, known as Nb-based SQUIDs, are employed in a variety of applications, including biomagnetic imaging and magnetoencephalography (MEG). SQUIDs can have detection limits as low as femtotesla levels.[52]

**Nanobridge Josephson Junctions:** These Nb-based junctions are employed in terahertz and microwave radiation ultrasensitive detection. Limits of detection may lie in the picowatt range.[53]

**Nanomechanical Resonators:** Force sensing and ultrasensitive mass detection are possible using Nb-based resonators. Limits of detection may fall within the attogram range.[54]

**Superconducting Transition Edge Sensors (TES):** Cryogenic detectors that measure extremely low-energy particles like photons and electrons employ Nb-based TES. Limits of detection may fall into the sub-electron volt region.[55]

**Nanowire Sensors:** Nb-based nanowire sensors have been developed for detecting single photons and electrons. Detection limits can be in the single-photon or single-electron regime.[56] Here's a table summarizing the information (Table 1).

# 9 Niobium compounds

In many ways, niobium is similar to tantalum and zirconium. It reacts with most nonmetals at high temperatures, with fluorine at room temperature; with chlorine at 150 °C and hydrogen at 200 °C, and with nitrogen at 400 °C, with products that are frequently interstitial and non-stoichiometric.[61,62] The metal begins to oxidize in air at 200 °C.[63] Acids like hydrochloric, sulfuric, nitric, and phosphoric acids cannot corrode it .[5] Hot, concentrated sulfuric acid, hydrofluoric acid, and hydrofluoric/nitric acid mix all destroy niobium. Hot, saturated alkali metal hydroxide solutions also damage it.[64] Niobium may exist in all formal oxidation states, ranging from +5 to −1, but it is most frequently found in compounds in the +5 state.[65] Nb–Nb bonding is often seen in compounds with oxidation levels lower than 5+. Niobium alone displays the +5-oxidation state in aqueous solutions. Due to the precipitation of hydrous Nb oxide, it is also very susceptible to hydrolysis and hardly soluble in diluted solutions of hydrochloric, sulfuric, nitric, and phosphoric acids.[66] Because of the development of soluble polyoxoniobate species, Nb(V) is also somewhat soluble in alkaline solutions.[67,68]

## 9.1 Oxides, niobates and sulfides

Niobium forms oxides in the oxidation states +5 ($Nb_2O_5$),[+4 ($NbO_2$), and the rarer oxidation state, +2 (NbO).[69] The most common is pentoxide, a precursor to almost all niobium compounds and alloys.[70] Niobates are generated by dissolving the pentoxide in basic hydroxide solutions or by melting it in alkali metal oxides. Examples are lithium niobate ($LiNbO_3$) and lanthanum niobate ($LaNbO_4$). The lithium niobate has a trigonally distorted perovskite-like structure, whereas the lanthanum niobate contains lone $NbO_4^{3-}$ ions.[71] The layered niobium sulfide ($NbS_2$) is also known.[61] Materials can be coated with a thin film of niobium(V) oxide chemical vapor deposition or atomic layer deposition processes produced by the thermal decomposition of niobium(V) ethoxide above 350 °C.[72,73]

Niobium sulfides, especially niobium disulfide ($NbS_2$), have caught the eye of scientists due to their fascinating electrical and electrochemical properties. These materials are key players in electrochemical sensors because they conduct electricity, kickstart reactions, and stay strong even in tough chemical conditions. They're like the reliable MVPs that keep the sensor game strong, no matter what challenges come their way.[74] Think of niobium sulfides as the superstars of electrochemical sensing. They might be the primary component of sensors or the igniting agents. Consider niobium disulfide – it functions similarly to a Swiss Army knife in terms of detection. Scientists are finding that it is incredibly effective in identifying a wide range of objects, including hydrogen processes and particular biomolecules.

It's similar like having a reliable lab partner that is always up to take on any detection challenge that comes your way.[75] Altogether, niobium sulphides provide some exciting prospects for enhancing the performance and usefulness of electrochemical sensors. This might pave the way for important developments in sensing technologies that affect several academic disciplines and industries. It seems like you are opening a treasure mine of opportunity to learn new things and make progress in the field of sensor technology.[76] Although less common than niobium sulphides, niobium niobates, such as potassium niobate ($KNbO_3$) and lithium niobate ($LiNbO_3$), are still valuable in electrochemical sensors. Their special combination of skills makes them effective at many other kinds of work, including detection. It works like having a backup plan in your toolbox – you might not need it all the time, but when you do, it comes in handy.[77] These materials are multifunctional electrochemical sensor equivalents to Swiss Army knives. Niobium niobates have several uses, such as electrode bases, electrolytes, and sensors themselves. Their characteristics that can be customized, stability, and adaptability to various settings make them an ideal team for sensor development. It functions similarly to a dependable, multipurpose instrument that you may use for whatever activity you throw at it.[78] Lately, researchers have been getting pretty excited about what niobium niobates could bring to the table in electrochemical sensing. They're looking into how these materials could make waves in areas like environmental monitoring, biomedical diagnostics, and energy storage. Sure, they might not have been in the spotlight as much as niobium sulfides, but they're definitely catching people's attention as a promising way to push forward the field of electrochemical sensing. It's like discovering a hidden gem – maybe not as well-known, but full of potential waiting to be uncovered.[79] Niobium oxide-based materials, like niobium pentoxide ($Nb_2O_5$) and niobium dioxide ($NbO_2$), have some special qualities that make them stand out for sensor applications, especially in electrochemical sensing. It's like they have a secret ingredient that makes them perfect for the job. These materials offer a blend of properties that researchers find really appealing for building sensors that can detect all sorts of things. So, they're kind of like the unsung heroes of the sensor world, quietly making a big impact behind the scenes.[74] Niobium oxide materials are like all-in-one tools for electrochemical sensors, serving as electrodes, electrolytes, or catalysts. With high surface area, great conductivity, stability, and compatibility, they're perfect for advancing sensor tech.[80] Recently, niobium oxides have attracted a lot of interest for use in electrochemical sensing applications, especially in areas such as environmental monitoring, biological diagnostics, and energy storage. They seem to be stepping into the limelight and are ready to make a big impact in these important areas.[81]

# 10 Applications of Nb-based materials

## 10.1 Lithium-ion battery

Lithium-ion batteries (LIBs) form the basis of portable gadgets and power systems since they provide crucial features like long lifespan, high energy density, and environmental sustainability that are necessary for our daily activities. The typical LIB setups consist of graphite anodes and $LiCoO_2$ cathodes. Through the electrolyte, lithium ions go from the cathode to the anode during charging and back again during discharge. As a result, LIBs successfully power our devices every day, ensuring their seamless operation.[82] Notwithstanding their commercial success, lithium-ion batteries still have drawbacks, such as low capacity and safety concerns. Developing better, more effective electrode materials is an essential strategy to address these issues.[83] Materials based on nickel have attracted a lot of interest due to their noteworthy advantages in terms of capacity and safety. Lithium-ion batteries (LIBs) are designed to prevent the creation of a passivated solid electrolyte interface (SEI) layer because their redox potentials (1.0–2.0 V) line up with the lowest unoccupied molecular orbital (LUMO) of the organic liquid carbonate electrolyte. Because of their polyvalent properties, Nb-based materials usually show greater capacitance when compared to conventional $Li_4Ti_5O_{12}$ (140 mAh g−1).[84]

Many researches are now investigating the use of Nb-based materials, with a primary focus on their potential use as electrode materials for lithium-ion batteries (LIBs). Achieving stable morphological structures and suitable ion transport routes is crucial when designing LIB electrode materials. For example, Shu et al. manufactured $K_2Nb_8O_{21}$ nanotubes (wall thickness of 40 nm and outer diameter of 160 nm) and $K_2Nb_8O_{21}$ microtubules (wall thickness of 500 nm and 2 μM) by carefully controlling the voltage and spinning speed during electrostatic spinning.[85] Its crystal structure is made up of $NbO_6$ octahedra and has an orthogonal tungsten bronze arrangement. The remaining Nb and K atoms fill the pentagram tunnels, although Nb atoms mostly occupy the centers of eight planes locally. The redox processes of $Nb^{5+}$/Nb4+ and $Nb^{4+}$/$Nb^{3+}$ are represented by the peaks seen at around 1.61 and 0.70 V, respectively. As an anode material for lithium-ion capacitors (LICs), $K_2Nb_8O_{21}$ has been found to have high structural stability (with 80.3 %

capacity retained after 5,000 cycles) and electrochemical reversibility, demonstrated by periodic lattice changes, through *in situ* XRD and transmission electron microscopy (TEM). Additionally, the Randles–Sevcik equation may be used to calculate the $Li^+$ diffusion coefficients from the findings of cyclic voltammetry (CV).[86] More precisely, Ip is proportional to the square root of the sweep rate v0.5, so the $Li^+$ diffusion coefficient ($DLi^+$) can be calculated based on the Randles–Sevcik equation:

The surface area of the electrode is represented by S in the equation, the $Li^+$ concentration is represented by C, and the number of electrons transported during the reaction is indicated by *n*. This equation indicates that because of their large specific surface area and short ion transport channel, nanotubes perform better electrochemically. Nb modification for solid electrolytes has also been investigated, in addition to its use as electrode materials. For instance, Markovic and colleagues [87] introduced Nb doping in garnet $Li_7La_3Zr_2O_{12}$, not as the primary energy storage material, but to stabilize the diffusion interface of Li+ (see Figure 3).[87]

$$IP = 2.69\times10^5 \times n^{1.5} \times SCD^{0.5}v^{0.5} \qquad (1)$$

## 10.2 Sodium ion battery

More and more people are beginning to see sodium-ion batteries (SIBs) as a viable alternative for large-scale energy storage since they have a basic storage mechanism in common with lithium-ion batteries (LIBs). Their cheaper price and the vast deposits of sodium are the main causes of this.[88] Notwithstanding their promise, issues including sluggish $Na^+$ diffusion kinetics and low energy density have prevented sodium-ion batteries (SIBs) from progressing as quickly as they could. These problems result from the

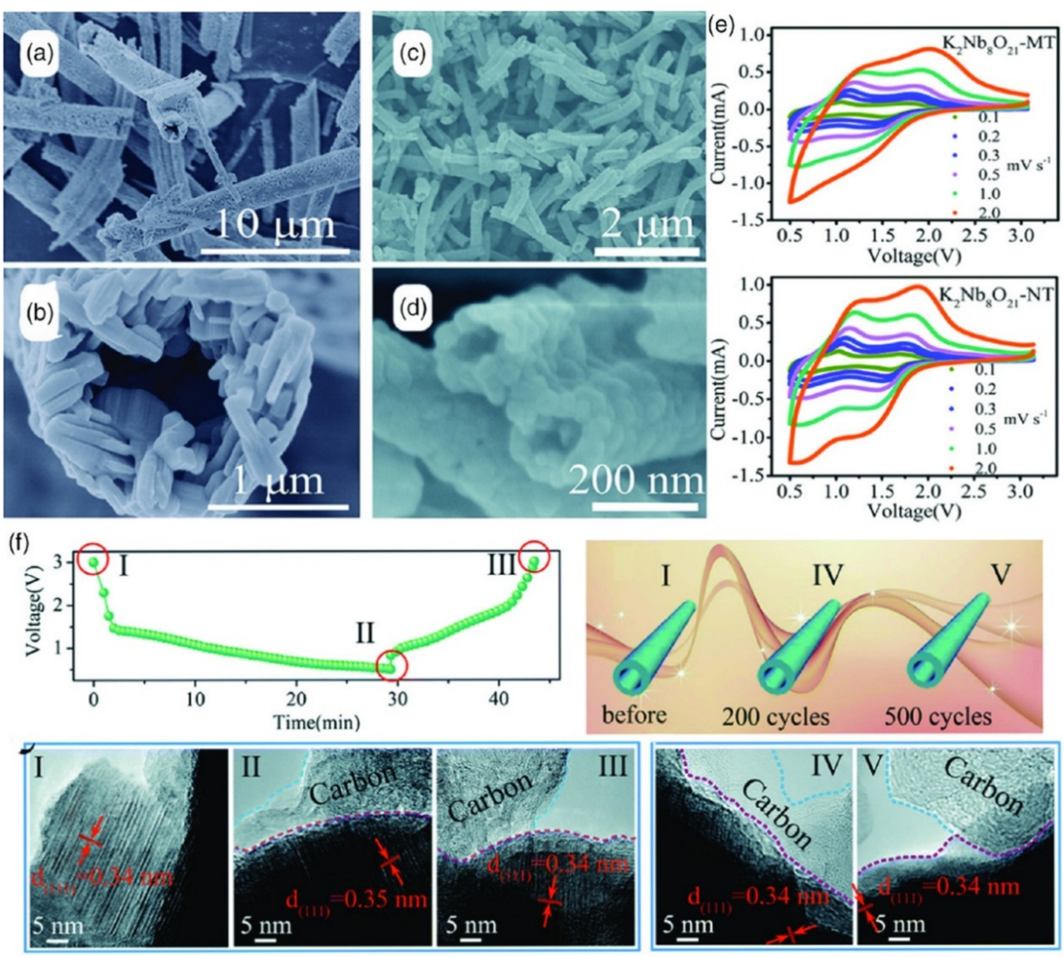


**Figure 3:** Morphological characterization and cyclic voltammetry (CV) analysis of $K_2Nb_8O_{21}$ materials: (a) and (b) show SEM images of $K_2Nb_8O_{21}$-MT, while (c) and (d) depict $K_2Nb_8O_{21}$-NT. The cyclic voltammetry (CV) results for both materials are presented in (e), (f) provides HRTEM images of $K_2Nb_8O_{21}$-NT at different lithiated/delighted states: Pristine, discharge to 0.5 V, recharge to 3.0 V, after 200 cycles, and after 500 cycles.[85]

sodium ion's ($Na^+$ = 1.02 Å) bigger size than that of the lithium ion ($Li^+$ = 0.76 Å).[89] Consequently, materials based on Nb that have low strain in energy storage and lattice channels may find application in SIB. Based on the idea of inherent benefits, enhancing material stability and active Sodium-ion batteries (SIBs) might benefit from the use of Nb-based materials due to their minimal strain on energy storage and lattice channels. Even if they have inherent benefits, current research aims to improve material stability and maximize the number and usage of active sites. Zhou et al., for example, created 1D nanofibers (T-$Nb_2O_5$@C) with ultra-small T-$Nb_2O_5$ crystals enclosed in them, which showed superior electrochemical performance. In addition to preventing T-$Nb_2O_5$ nanoparticle agglomeration, reducing material crushing, and improving cyclic stability (maintaining constant capacity over 5,000 cycles), the carbon matrix also increases electrical conductivity.[90] The optimal capacitive properties of $Nb_2O_5$ are maximized by the uniform distribution of ultrafine nanoparticles (6–7 nm), leading to increased material capacitance (which may reach 229 mAh g–1 at 0.1 A g–1). Apart from nano-crystallization and carbon inclusion, lattice design is a useful tactic to maximize the performance of Nb-based materials. In sodium-ion batteries (SIBs), high-crystallinity nanomaterials and amorphous membrane materials have shown very high capability. Yu and co-workers [91] developed an amorphous hydrogenated $Nb_2O_5$ film that was produced on a Nb substrate and had a self-sequencing porous structure (15–20 nm). With its ordered porosity structure, this novel design makes direct contact between the substrate and the $Nb_2O_5$ layer, which improves the efficiency of ion transport. Moreover, the structure guarantees the elastic adherence of the nanoporous film to the flexible substrate, avoiding the loss of structural integrity brought about by the repetitive encasement and disembodiment of $Na^+$ ions. Furthermore, hydrogenation raises the insulating $Nb_2O_5$'s electrical conductivity (measured at $3.0 \times 10^{-3}$ S $cm^{-1}$) relative to its non-hydrogenated equivalents. The electrode materials' durability and $Na^+$ storage activity is effectively promoted by structural optimization (amorphous), composition regulation (hydrogenation), and morphology design (ordered nanopores). This is demonstrated by the electrode materials' remarkable combination of large capacitance (185 mAh g–1 at 0.5 C) and excellent cycling stability (see Figure 4).[92]

## 10.3 Lithium–sulfur battery

Li–S is one of the main candidates to surpass lithium-ion batteries because of its high theoretical energy density of 2,500 Wh kg^-1.[93,94] Li–S must first overcome a number of obstacles before it can be extensively used, such as sluggish transition kinetics of intermediate LiPS, insulating concerns with sulfur and its lithiated byproducts, and shutdown behavior caused by high PS solubility.[95] Porous carbon has gained recognition as a useful material for hosting Li–S

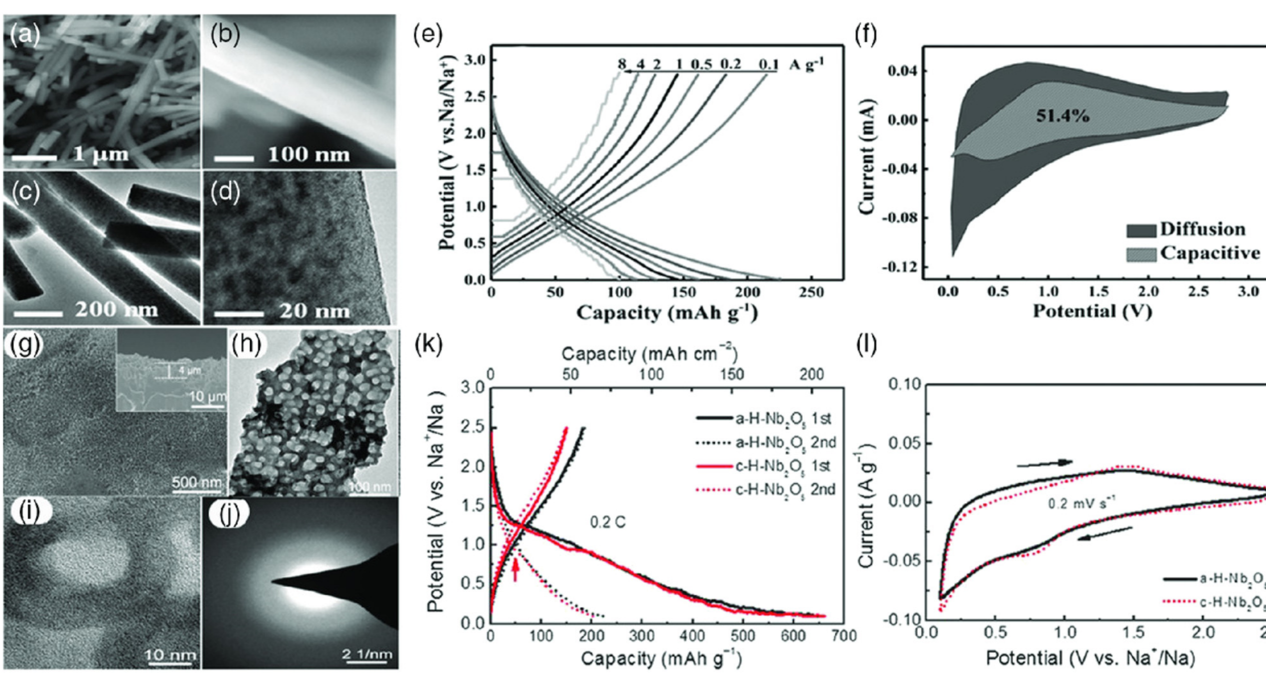


**Figure 4:** Morphological and electrochemical analysis of T-$Nb_2O_5$@C and T-$Nb_2O_5$ membrane: (a, b) SEM images, (c, d) shows TEM, and (e, f) present GCD and CV data for T-$Nb_2O_5$@C [90], for the T-$Nb_2O_5$ membrane, (g, h) display SEM, (i, j) show TEM, and (k, l) exhibit GCD and CV data.[90]

systems due to its enhanced electron conductivity and ability to effectively retain sulfur inside micropores.[96] However, nonpolar carbon materials' poor affinity for LPS prevents them from effectively immobilizing sulfur, which results in reduced sulfur dynamics, insufficient suppression of shuttle effects, and decreased coulomb efficiency.[97] Polar Nb-based materials have a strong affinity for LPS and good chemical stability, which makes them useful sulfur accelerators with significant benefits for improving Li–S electrochemical performance. Nb-based materials may effectively promote electron/ion transport and accelerate sulfur fixation in Li–S systems by regulating crystallinity and defect structure. The addition of vacancies to niobium-based materials decreases the activation energy of sulfur redox reactions and enhances the chemical interaction with LPS. Chen et al. created a strawberry-like nanostructure in carbon nanosphere micropores by introducing ultrafine $Nb_2O_5$-x nanoclusters with an amorphous structure and plenty of oxygen vacancies. The Li–S batteries' performance was improved by this invention. Furthermore, the contact between $Nb_2O_5$ and LPS was enhanced by the amorphous and faulty structures, and the catalytic activity of LPS conversion was further enhanced by the presence of oxygen vacancies.[65] Additionally, the composite structure with integrated nanoclusters can function as a rich active interface for limiting and converting LPS, regulating sulfur distribution, improving sulfur usage, and providing a conductive framework for speeding electron/ion transfer. As seen in Figure 5, these developments add up to better electrochemical performance.[98]

Because niobium-based materials are polar and have a significant affinity for LPS, creating materials with cavity architectures has great promise for use in Li–S batteries. Wang and co-workers [99] combined highly conductive graphene oxide with hollow Nb2O5 microspheres (2–3 μM) to create M-$Nb_2O_5$@rGO, a hybrid shell material. The ionic and electronic conductivity of this substance is quite good. Fast Li + transmission and stable chemical contact with PS are made possible by $Nb_2O_5$'s polarity, which helps convert PS into $Li_2S$. Due to the huge pore space, sulfur volume growth during energy storage is greatly reduced, even at high sulfur loads. Furthermore, the redox kinetics of $Nb_2O_5$ are improved when rGO is present around the electrode.

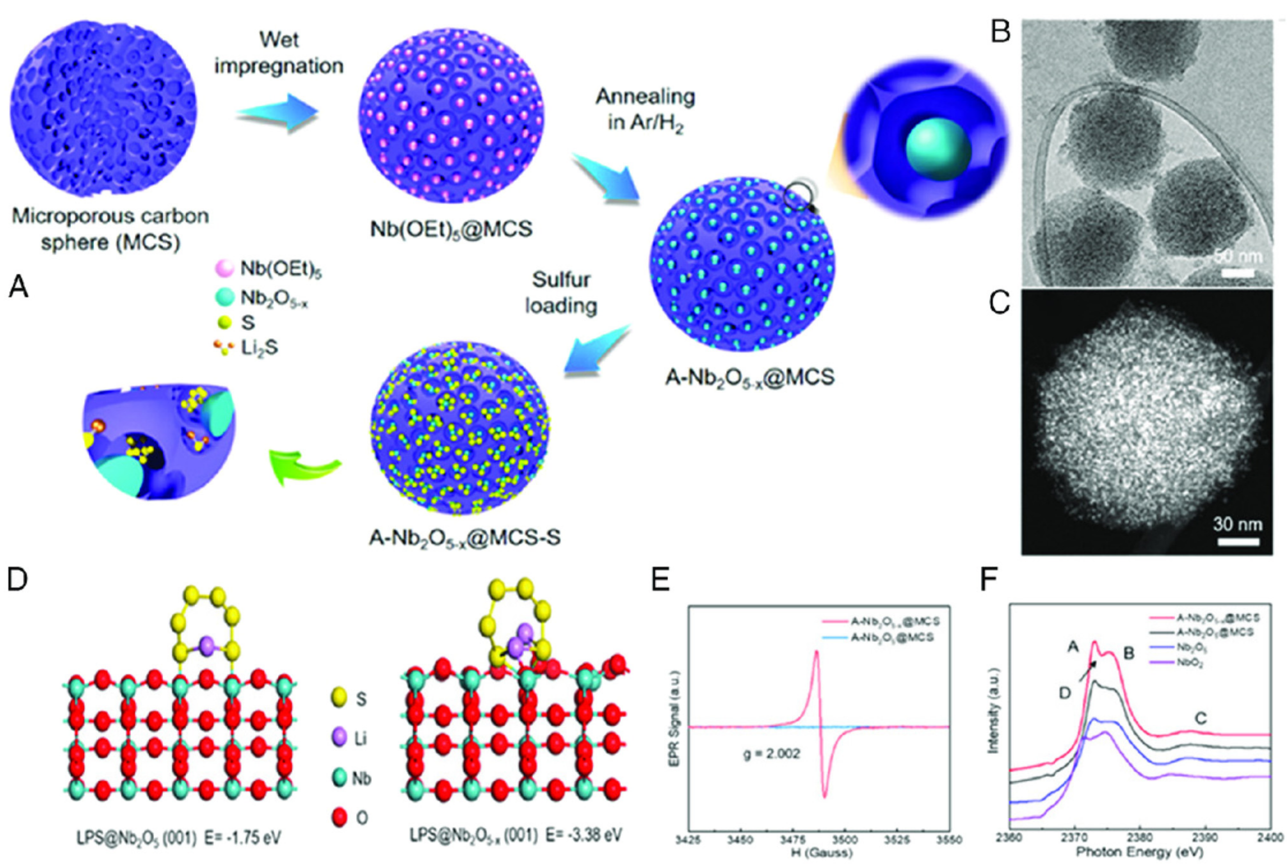


**Figure 5:** Synthesis, characterization, and analysis of A-$Nb_2O_5$–x@MCS: (A) we'll start with how we made it, (B, C) check out some cool microscope pictures of A-$Nb_2O_5$–x@MCS, (D) We've also got diagrams showing the best shape and how it reacts with Li2S6, (E) take a look at the fancy pattern we found using EPR, and (F) some spectra stuff we measured using X-ray.[65]

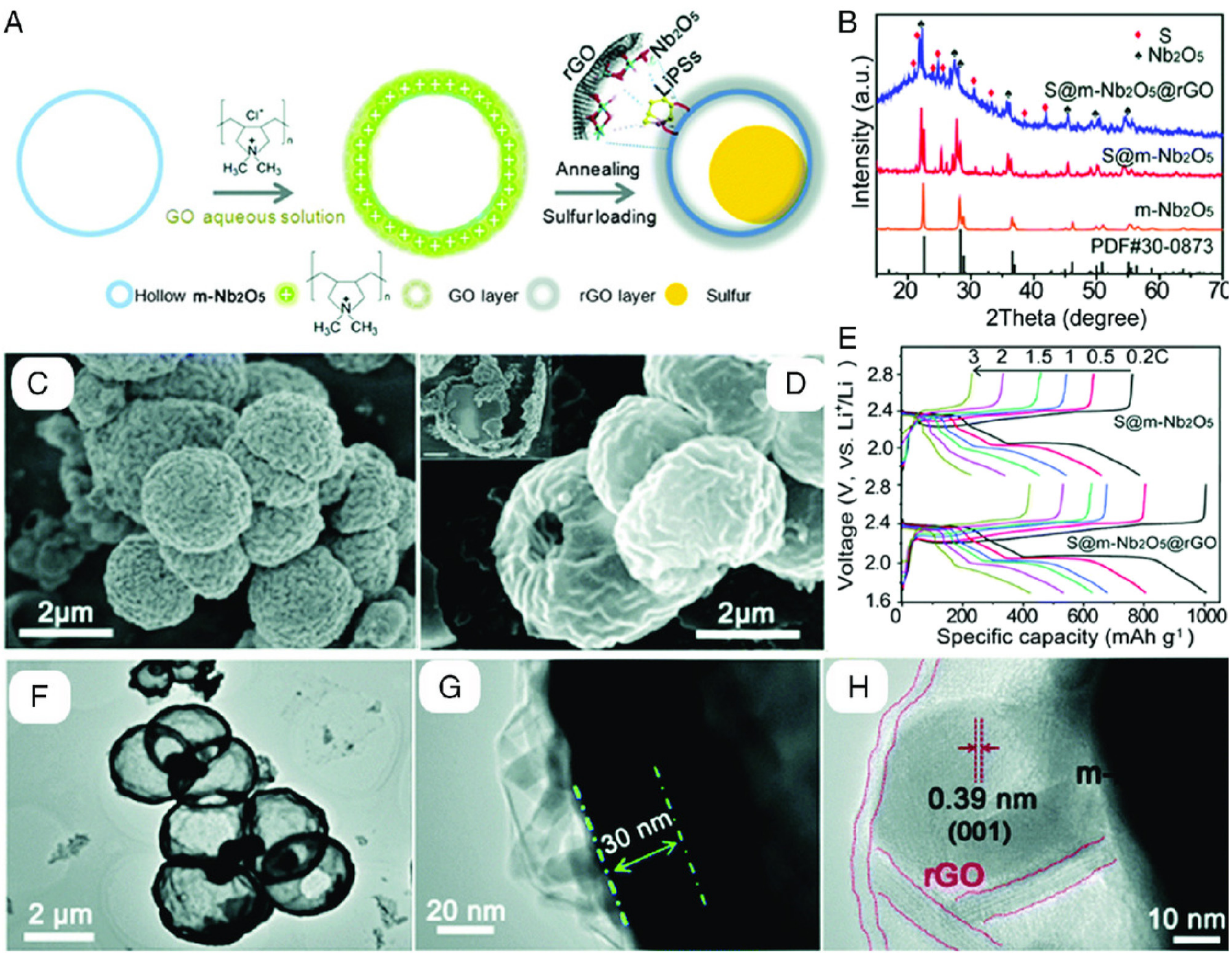


**Figure 6:** Synthesis and characterization of $Nb_2O_5$@rGO: (A) synthetic process, (B) XRD, (C,D) SEM, (E) GCD, (F,H) HRTEM of $Nb_2O_5$@rGO.[99]

The principal electrode material of Li–S batteries, M-$Nb_2O_5$@rGO, reaches a capacitance of 1,004.5 mAh g^-1 at a current density of 0.2 C, as shown in Figure 6, because of these design benefits.[100]

## 11 Conclusions

In conclusion, this review has highlighted the importance of niobium in the advancement of electrochemical technology. We have highlighted niobium's remarkable conductivity, stability, and biocompatibility by a full examination of its distinct physical and chemical properties, all of which contribute to its versatility in a wide range of applications. Its efficacy in electrochemical sensors, energy storage systems, and other electrochemical technologies demonstrates its potential to transform industries ranging from healthcare to environmental management. Because of their exceptional electrochemical performance and versatility, niobium-based materials hold promise for the creation of more efficient, dependable, and sustainable sensors. Their use in energy storage devices, such as batteries and supercapacitors, also underscores their importance in next-generation energy technology. Moving forward, it is expected that continued research and technical improvements will broaden the spectrum of niobium's applications, resulting in even more inventive and impactful usage in electrochemical technology. As the area advances, niobium will definitely play a larger role in stimulating new research, upgrading existing systems, and tackling global concerns. These advancements will not only help to progress electrochemical technology but will also open up new pathways for multidisciplinary research, stimulating creativity in a variety of scientific and industrial sectors.

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