Subject: Review Decision – Manuscript ID: FT2025-191
Title: *Development and Characterization of Copper-Nickel (Cu/Ni) Coil-Based Cryogenic Temperature Sensors via Electroplating Method*

Dear Author(s),

Thank you for submitting your manuscript to the Forward Together 2024 International Conference. Your study offers a timely and innovative contribution to low-temperature sensor development using Cu/Ni coils fabricated through electroplating. The paper demonstrates detailed experimental methods and comprehensive data analysis relevant to cryogenic applications.

After careful review by two independent reviewers, we regret to inform you that the manuscript requires **major revision** before being considered for publication in the conference proceedings. Below, we include their comments and recommendations for improvement.

Reviewer 1 Comments

1. Title
Judul cukup informatif, namun belum cukup menonjolkan aspek kebermanfaatan sosial atau inovasi aplikatif. Disarankan untuk menambahkan unsur aplikatif, misalnya:
"Electroplated Cu/Ni Coil Sensors for Cryogenic Applications: Low-Cost Temperature Monitoring in Industrial and Scientific Settings"

2. Abstract
Abstrak telah mencakup tujuan, metode, hasil, dan kesimpulan. Namun, perlu:

- Diringkas dan dibuat lebih padat.
- Tambahkan informasi kuantitatif utama, seperti sensitivitas tertinggi dan hysteresis loss.
- Hindari penggunaan istilah teknis berlebihan seperti "face-centered cubic" tanpa penjelasan.

3. Introduction
Latar belakang cukup kuat, namun dapat diperbaiki dengan:

- Menambahkan gap riset secara eksplisit: apa yang belum dilakukan oleh studi sebelumnya.
- Mengaitkan manfaat sensor ini dengan agenda SDGs atau tema inklusi sosial.

4. Methods
Metode sangat rinci dan komprehensif. Namun:

- Sebaiknya diberikan skema visual sederhana dari prosedur eksperimen (misalnya sebagai diagram alur).

- Tambahkan penjelasan mengapa pemilihan tegangan 4.5 V dan 6.0 V menjadi titik fokus analisis.

5. Language Usage
Bahasa Inggris secara umum baik, tetapi beberapa kalimat perlu diperpendek agar tidak membingungkan pembaca. Sebaiknya gunakan gaya penulisan yang konsisten (hindari campuran antara kalimat pasif dan aktif).

Reviewer 2 Comments

1. Relevance to Conference Theme
Topik artikel sangat relevan dengan sub-tema *Applied Physics* dan *Innovation in Physics Education*. Akan lebih kuat jika penulis menjelaskan potensi pengembangan sensor ini dalam pengajaran fisika atau pendidikan vokasi.

2. Results and Discussion
Data hasil sangat kaya dan visualisasi sangat membantu. Namun:

- Diskusi hasil kadang berulang. Ringkas narasi yang menjelaskan grafik agar fokus pada interpretasi data.
- Tambahkan perbandingan hasil dengan sensor sejenis lain selain PT-100 (misalnya, sensor thermocouple).

3. Data Visualization
Visualisasi sangat informatif. Agar lebih baik:

- Beri judul lengkap pada grafik (misalnya “Figure 4: Voltage-Temperature Characteristics of Cu/Ni Sensors”).
- Gunakan satu tabel ringkasan performa sensor (sensitivity, response time, hysteresis, voltage range).

4. Conclusion
Kesimpulan sudah menyampaikan temuan utama, tetapi saran praktis belum muncul secara kuat. Disarankan untuk menambahkan:

- Implikasi praktis dari penggunaan sensor ini di industri (misalnya: cryo-preservation, LNG storage, aerospace).
- Rencana pengembangan selanjutnya: misalnya peningkatan sensitivitas dengan material tambahan.

5. Novelty and Originality
Artikel menunjukkan pendekatan eksperimental baru pada sensor suhu rendah berbasis elektroplating. Perlu ditegaskan bahwa sensor ini merupakan alternatif murah dan dapat dirancang fleksibel untuk berbagai aplikasi.

Editor's Comments

I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following **major revision** and modification. I invite you to resubmit your manuscript after addressing the comments above.

Please resubmit your revised manuscript by **28 April 2025** by the latest (the postpone will delay the publication of the proceeding book). When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please outline every change made in response to their comments (giving **yellow highlight colour** and/or write **cover letter explaining the changes**) and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

To submit your revised manuscript, please send to:
https://s.id/RevisedArticleForwardTogether2024

NOTE: Upon submitting your revised manuscript, please upload the source files for your article (**MS Word**). We cannot accommodate PDF manuscript files for production purposes. We also ask that when submitting your revision, you follow the proceeding templates.

Thank you for your contribution and your engagement with Forward Together 2025. We look forward to your revised submission.

Best regards,

Prof. Maila D.H. Rahiem, MA., Ph.D.
Chief Editor, ForwardTogether 2024
https://forwardtogether.uinjkt.ac.id/en

~~Development and Characterization of Copper-Nickel (Cu/Ni) Coil-Based Cryogenic Temperature Sensors~~ via ~~Electroplating Method~~

Electroplated Cu/Ni Coil Sensors for Cryogenic Applications: Low-Cost Temperature Monitoring in Industrial and Scientific Settings

Commented [MT1]: Menjawab reviewer 1: Disarankan menambahkan unsur aplikatif misalnya: Electroplated Cu/Ni Coil Sensors for Cryogenic Applications: Low-Cost Temperature Monitoring in Industrial and Scientific Settings

Abstract. Cryogenic temperature sensors play an essential role in various scientific and industrial applications that require precise low-temperature measurements, such as in medicine, food technology, aerospace, and quantum physics. This study aims to develop a temperature sensor based on copper-nickel (Cu/Ni) wire fabricated through an electroplating method with variations in electrode voltage of 0 V, 4.5 V, 6.0 V, and 7.5 V. The plating process was carried out using a $NiSO_4$, $NiCl_2$, and H_3BO_3 electrolyte solution at 60 °C. The sensors were tested using liquid nitrogen across a cryogenic temperature range and analyzed for performance parameters such as response time, voltage range, sensitivity~~,~~ ~~temperature coefficient of resistance (TCR)~~, and hysteresis loss.

Results indicate that all sensors responded to temperature changes from −160 °C to 0 °C. The pure Cu sensor exhibited the fastest response time and the largest voltage range, that are 180s and 0.02 V; however, it showed instability against temperature variations. The sensor deposited at V_dep = 4.5 V demonstrated a response time of 300 seconds.

There was a tendency for the voltage range to decrease with increasing deposition voltage. The minimum voltage range was observed in the sensor deposited at 6 V, with a value of 0.01 V, while the widest range of 0.02 V corresponded to the pure Cu. An increase in deposition voltage tends to enhance sensor sensitivity.The sensor fabricated at V_dep = 6 V exhibited higher sensitivity; however, the trend of sensitivity decrease with temperature was smaller compared to the sensor deposited at 4.5 V. Moreover, increasing the deposition voltage reduced hysteresis losses. The hysteresis loss for the sensor deposited at 4.5 V was 0.0052 V, while that for the sensor deposited at 6.0 V was 0.0023 V. Thus, higher deposition voltage resulted in a more stable sensor response to temperature variations.

Comparison with Ag, Cu, and Pt-100 sensors revealed that the resistance change of Cu/Ni sensors deposited at 4.5 V and 6.0 V was significantly smaller than that of silver, copper, and Pt-100 sensors.

Keywords: Cryogenic temperature, Cu/Ni coil, sensitivity, hysteresis loss.

INTRODUCTION

Cryogenic temperature sensors are utilized across various sectors, particularly in food technology, enabling the rapid freezing of food products. This technique preserves the texture and quality of the food while significantly extending its shelf life [1] Similar applications are found in preserving biological products or additives, such as probiotics and livestock semen [2].

In the medical field, cryogenic sensors are integral to technologies like Magnetic Resonance Imaging (MRI), which uses liquid helium to cool superconducting magnets [3]. Cryogenic treatment is also employed for tissue freezing in therapeutic applications. In industrial settings, especially the gas industry, these sensors are crucial for measuring the temperature in storage tanks of liquefied gases, including during transportation [4]. In biological research, cryogenic sensors help maintain optimal temperatures for storing cells, tissues, or organs [5].

In the aerospace sector, cryogenic temperature control is essential for managing components that operate in extremely low-temperature environments [6]. Similarly, in laboratory research, cryogenic sensors play a critical role in experiments sensitive to temperature fluctuations, such as those involving superconductivity, particle physics, and quantum research [7]. Materials used for low-temperature sensors must exhibit thermal stability, good electrical conductivity, and a responsive change in resistance or voltage with temperature variation. Common materials for temperature sensors include platinum (Pt), copper (Cu), nickel (Ni), constantan, specialized metal alloys such as germanium and Cernox, as well as semiconductors like glass diodes, silicon, and superconducting materials [8].

Nickel, in particular, is highly suitable for low-temperature sensors due to its high-temperature coefficient of Resistance (TCR), reaching up to 0.00672/°C. It is cost-effective, easy to fabricate in various forms such as wires, thin films, or spirals, and offers precision at temperatures below 300 K [9]. Also, nickel is resistant to corrosion and oxidation at low temperatures and enables temperature reading without requiring complex electronic systems [10]. Nickel-coated copper (Cu/Ni) wire exhibits excellent ~~enhanced~~ flexibility, allowing it to be coiled, facilitating assembly and integration with other electronic components [11]. At the interface between copper and nickel, ~~does not present significant issues, as both materials possess a face-centered cubic (fcc) crystal structure, which ensures structural compatibility [11]~~ a strong bond is formed due to the similar atomic sizes of the two materials, with nickel having a radius of 121 pm, slightly smaller than copper's 138 pm [11].

Mechanically, Cu/Ni wire demonstrates increased pliability, reducing the likelihood of damage [12]. As a temperature sensor, Cu/Ni wire is particularly suitable for measuring temperatures at specific points or localized areas (IST AG, n.d.). However, its wire form results in a smaller contact cross-sectional area. Additionally, the higher thermal mass of Cu/Ni wire leads to a slower response time. To address this, the number of coil turns ~~wire coil~~ should be increased ~~elongated~~ and ~~it's~~ the diameter should be reduced [13].

Electroplating is a more feasible and low-cost method for fabricating nickel-coated copper (Cu/Ni) wire due to its low operational cost, high quality, simple equipment requirements, and the ability to produce ~~high-quality coatings~~. This technique is particularly suitable for complex geometries, such as wires and coils, requiring uniform and adherent metal layers.

~~In addition to its practicality, copper and nickel exhibit strong material compatibility. Both are face-centered cubic (FCC) metals with nearly identical atomic radii, which promotes good metallurgical bonding. This structural similarity allows for forming a stable interfacial layer, which enhances the mechanical and chemical stability of the composite wire.~~

Although previous studies have focused on the use of various materials for low-temperature sensors, such as Pt, Cu, Ni, and constantan, there is still a notable lack of research that deeply explores the use of copper-nickel (Cu/Ni) wire, particularly for cryogenic temperature sensors. Moreover, although nickel is well known for its high Temperature Coefficient of Resistance (TCR), the effect of deposition voltage variation during the electroplating process on sensor performance at cryogenic temperatures remains unclear. This study addresses this gap by investigating how variations in electrode voltage (0–7.5 V) influence response time, voltage range, sensitivity, and hysteresis loss at cryogenic temperatures, thus providing a more comprehensive understanding of the potential of Cu/Ni as an alternative material for cryogenic temperature sensors.

~~In this study, Cu/Ni wire was fabricated using electroplating with electrode voltage variations ranging from 0 to 7.5 volts. The resulting wires were subjected to material characterization and performance testing as low-temperature sensors. The performance evaluation included voltage range measurement, sensitivity, temperature coefficient of resistance (TCR), and hysteresis. Prior studies have shown that electrodeposition parameters such as voltage, temperature, and electrolyte composition can significantly influence the properties of the deposited layer and the resulting sensor performance~~ [14].

The development of Cu/Ni wire-based cryogenic temperature sensors contributes to the Sustainable Development Goals (SDGs) by improving equitable access to advanced medical technologies (SDG 3: Good Health and Well-being), fostering innovation and industrial development through the utilization of locally available resources (SDG 9: Industry, Innovation, and Infrastructure), and supporting sustainable and responsible production systems (SDG 12: Responsible Consumption and Production). Beside that, this sensor provides a low-cost alternative and can be flexibly designed for various applications.

In the context of vocational education, the electroplating topic and the application of cryogenic temperature sensors is highly relevant, as it provides practical skills that are in high demand in the engineering and manufacturing industries, particularly in the fields of materials science and sensor technology [1],[2]. By imparting knowledge and skills in electroplating and cryogenic temperature sensors, vocational education can prepare the younger generation to contribute to the rapidly growing industrial sector, while also enhancing domestic research and technological capacity [3].

EXPERIMENT

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The experimental procedure was carried out according to the scheme presented in Fig. 1.

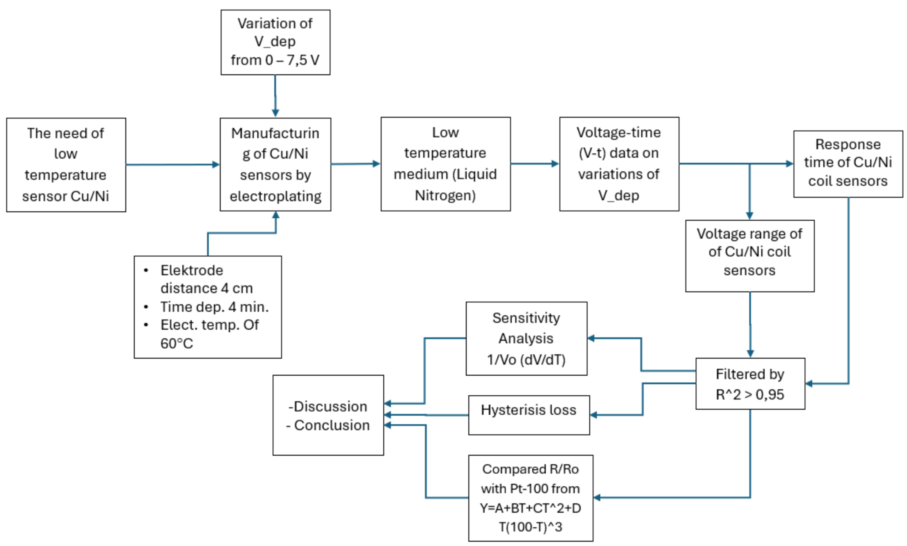

Figure 1. The experimental procedure employed in this research.

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Material Preparation

The initial step involves preparing materials such as copper wire coils, nickel plates, and an electrolyte solution consisting of $NiSO_4$ (260 g), $NiCl_2$ (60 g), H_3BO_3 (40 g), and deionized water (1000 mL).

Substrat Preparation

In the substrate preparation phase, the surfaces of the 0.5 mm copper wire and 10×1.5×0.01 cm^3 nickel plate were meticulously cleaned by rubbing them with a soft cloth impregnated with Autosol SM583 metal polish. Polishing continued with a soft cloth coated with toothpaste until the surfaces appeared shiny. Subsequently, the copper wire and nickel plate were washed with Sunlight detergent, rinsed with deionized water, and cleaned with 95% alcohol in an ultrasonic cleaner for 3 minutes. After drying, the copper wire was weighed using an Ohaus PR223/E balance [15].

Fabrication of Cu/Ni Wire Sample

To prepare the Cu/Ni wire samples, an electroplating reactor was utilized. The copper wire was coiled into a 5 mm diameter coil with 100 turns. The coil was placed at the cathode, 4 cm away from the nickel plate, which served as the anode. Both electrodes were immersed in an electrolyte composed of $NiSO_4$ (260 g), $NiCl_2$ (60 g), H_3BO_3 (40 g), and deionized water (150 mL) at a temperature of 60°C. Electroplating was performed at a voltage of 4.5 V for 4 minutes. During the electroplating process, the current was measured using a DCP-BTA vernier. This process was repeated for other substrates at electrode voltages of 6.0 V and 7.5 V. The applied voltage during electroplating was selected in the range of 4.5–7.5 V to ensure uniform deposition and minimize defects on film. Lower voltages resulted in slow growth, whereas higher voltages led to rough and porous layers. The chosen range provided an optimal balance between deposition rate and surface quality, which is critical for cryogenic sensor performance. After electroplating, the samples were removed, cleaned with deionized water in an ultrasonic cleaner for 3 minutes, and dried using a hair dryer [16].

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Data Acquisition

To obtain data on the response of the Cu/Ni coil samples as low-temperature sensors, the samples were gradually lowered into a liquid nitrogen thermos along with a TCA-BTA thermocouple at a rate of 1,07 cm/min and a sampling rate of 1 sample per second. The samples were lowered to the minimum measurable temperature by the thermocouple (approximately -165°C) and then raised back to their original position. The voltage response at both ends of the sample was measured using a VP-BTA voltage sensor, while the thermocouple response was recorded as temperature. The data were processed with the LabQuest Mini transducer and displayed on a computer screen using Logger Pro™ 3 software, which provided numeric, graphical, and data processing facilities [17].

Data Analysis

The numerical voltage data at different times (Vi,ti) and for different deposition voltages are crucial for developing electroplated material-based sensors. These data were ~~can be~~ used to determine ~~the quality of the~~ sensor quality, as well as the influence of the material's microscopic structure on sensor performance, including voltage range, sensitivity, and hysteresis losses. The R/R_0 value of the sample was compared with that of the Pt-100 sensor to assess the performance ~~of the produced sensor compared~~ to a commercially ~~available~~ sensor.

~~To determine~~ The voltage range was obtained by calculating the difference between the sensor voltage at the maximum and minimum temperatures was calculated:

$$\Delta V = V_{max} - V_{min} \tag{1}$$

For sensitivity, the semi-relative sensitivity to V_0 or the sensor voltage at 0°C was used:

$$S_T^V = \frac{1}{V_0}\frac{dV}{dT} \tag{2}$$

Hysteresis loss was determined by calculating the maximum voltage difference between the heating and cooling curves at the same temperature:

$$HL = \left(V_c - V_h\right)_{max} \tag{3}$$

Where HL, V_c, and V_h represent hysteresis loss, cooling voltage, and heating voltage, respectively.

To compare the temperature sensor performance with the Pt-100 sensor, the Callender-Van Dusen ~~following~~ equation was used **[….]**:

$$\frac{R}{R_0} = A + BT + C(T - 100)T^3 \quad (4)$$

where A, B, and C are constants. A determines the sensor sensitivity, B accounts for deviations from linearity, and C represents additional curve deviations. Ideally, A should be as large as possible, while B and C should be as small as possible. For the Pt-100 sensor, the constants are A = 3.91E-03, B = -5.78E-07, and C = -4.18E-12 [17].

RESULTS AND DISCUSSION

Voltage – Time Curve

Figure 1 illustrates the voltage-time response of the Cu/Ni sensor when immersed in liquid nitrogen, transitioning from 0°C to approximately -160°C, and subsequently warming back to 0°C. The characterization results demonstrate that Cu/Ni materials exhibit thermoresistive properties, where their electrical resistance varies with temperature. Deposition voltages of 0 V, 4.5 V, 6.0 V, and 7.5 V influence the sensor's output voltage levels but do not alter the general trend of the sensor's response to temperature changes [18]. The sensor's response to temperature variations is sufficiently sensitive and consistent, indicating the potential of Cu/Ni sensors for cryogenic temperature monitoring applications [19].

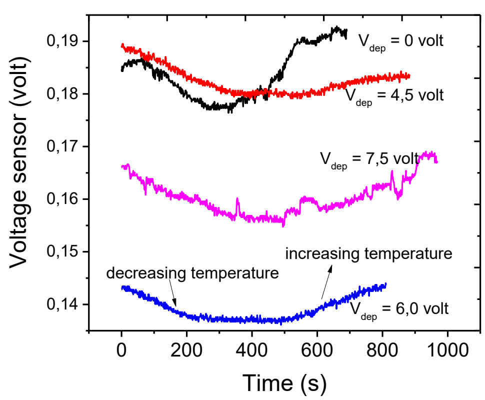

FIGURE 1. Voltage response of the Cu/Ni sensor during cooling and heating cycles in liquid nitrogen

Subsequently, the output voltage of the Cu/Ni sensor ranged from 0.145 V to 0.195 V, depending on the deposition voltage ~~applied during electroplating~~. Uncoated Cu sensors were able to respond to temperature changes but lacked stability. Sensors electroplated at 6.0 V exhibited the lowest minimum voltage and stable signal characteristics, whereas those electroplated at 7.5 V showed voltage fluctuations [20].

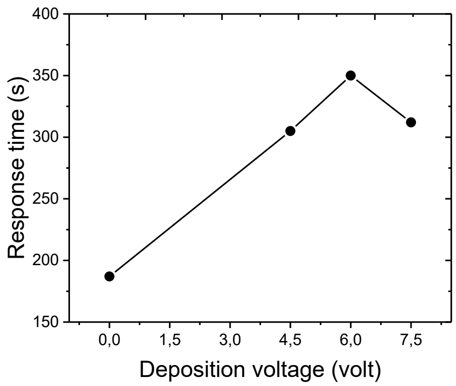

FIGURE 2. Response time of the Cu/Ni sensor during cooling from 0°C to -160°C.

~~Observations of The time required by for the sensor to reach the its minimum voltage, as shown in Fig. 2, indicate a significant effect of deposition voltage on response time. Pure Cu sensors (without Ni coating) exhibited the fastest response time, approximately 180 seconds. In contrast, the Cu/Ni sensors deposited electroplated at 4.5 V, 6.0 V, and 7.5 V required took about 300 s, 350 s, and 310 s, respectively, to reach their minimum temperature voltage [19]. This suggests that the electroplating process results in Cu/Ni layers with microstructural features that function as additional thermal resistances, slowing down the heat transfer process. The increased response time with higher deposition voltages is likely due to the growth of thicker or rougher layers, which increase thermal capacitance and impede cooling. Therefore, when designing temperature sensors, a balance must be sought between sensor sensitivity and response speed [18].~~

The time required to reach the minimum voltage, as presented in Figure 2, was significantly affected by the deposition voltage. The pure Cu sensor (without Ni coating) exhibited the fastest response time of approximately 180 s, while Cu/Ni sensors deposited at 4.5 V, 6.0 V, and 7.5 V required approximately 300 s, 350 s, and 310 s, respectively [19]. According to You et al., the increase in response time was attributed to the microscopic structure and surface morphology of the sensors, which introduced additional thermal barriers and reduced the heat transfer rate [18], [D].

Voltage Range

The voltage range is crucial as it directly impacts the accuracy and overall performance of the system. If the sensor voltage is to be converted to an ADC, a wider voltage range leads to a higher resolution on the ADC, resulting in more accuracy. A good sensor is one that has a voltage range close to the input voltage limit of the ADC, which is typically 0–5 V [21], [22].

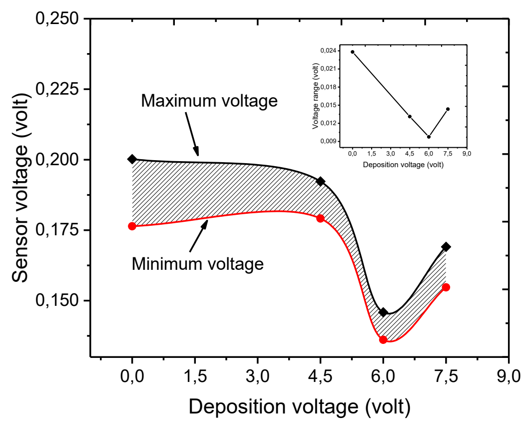

FIGURE 3. Characteristic of maximum and minimum sensor voltage and voltage range ~~of the Cu/Ni coil sensor at varying deposition voltages~~.

The inset graph indicates that the deposition voltage significantly affects the working voltage range of the Cu/Ni temperature sensor. ~~The sensor fabricated at a deposition voltage of 6.0 V exhibits the smallest voltage range, indicating a more stable and linear output but with a limited range. Conversely, sensors made at deposition voltages of 0 V, 4.5 V, and 7.5 V exhibit broader voltage ranges. These sensors are more suitable for applications requiring the detection of large temperature variations, although they may experience more fluctuations or signal instability [23], [24]~~.

The sensor deposited at V_dep = 6.0V exhibited the smallest voltage range of 0.01 V, indicating a limited measurement capability. In contrast, sensors deposited at Vdep = 0V, 4.5 V, and 7.5 V showed wider voltage ranges, with the widest range of 0.02 V observed at V_dep = 0V. In electronic measurement systems, a small voltage range generally results in lower precision but offers greater signal stability due to minimal fluctuations. Conversely, a larger voltage range provides higher measurement accuracy but lower precision, as greater signal fluctuations reduce stability. Nevertheless, all observed voltage ranges and maximum output voltages remained within the detectable range of the ADC (1–5 V), although signal amplification of approximately 20 times was still required [23], [24].

Voltage-Temperature Curve

Figure 4 illustrates that, generally, all the curves show an increase in sensor voltage as temperature rises, although with different slopes (sensitivities), depending on the deposition voltage ~~used during sensor fabrication~~. ~~The sensitivity and output voltage level of each sensor differ depending on its deposition voltage.~~

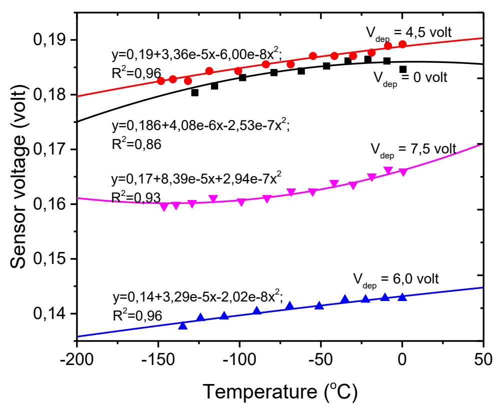

FIGURE 4. ~~Sensor response to temperature variations from -15°C to 0°C in the form of sensor voltage.~~ Voltage-Temperature characteristics of Cu/Ni Coil Sensors.

Commented [MT8]: Menjawab reviewer 2: Beri judul lengkap pada grafik (misalnya "Figure 4: Voltage-Temperature Characteristics of Cu/Ni Sensors.
Gambar yang lain juga sudah direvisi

The sensor fabricated with V_dep = 4.5 V exhibits the highest response to temperature changes. This is shown by the curve being at the top of the graph, as well as the highest gradient (slope) of the linear equation compared to the other sensors. ~~This condition indicates that at a deposition voltage of 4.5 V, the sensor's surface structure and morphology are optimal for detecting temperature changes.~~ Additionally, with the highest R^2 value (0.96), it indicates that the sensor's response to temperature changes is consistent, quite stable, and highly accurate [20],[21].

On the other hand, the sensor fabricated at V_dep = 0 V shows reasonably good performance but still underperforms compared to the V_dep = 4.5 V sensor. ~~This could be due to the lack of a Ni coating, which would have enhanced the electrode surface sensitivity.~~ This is likely due to the absence of the Ni layer, which could enhance the sensor's surface response to temperature changes. This is further supported the lowest R^2 ~~value~~ (0.86) suggests that the ~~measurement~~ data is more spread out around the regression line. This suggests that the sensor was unable to consistently respond to temperature changes in terms of the voltage output.

~~, likely due to the irregular structure of the sensor from the lack of Ni coating, resulting in less stable responses~~ [22],[23].

At higher V_dep values of 6 V and 7.5 V, the sensor output voltage tends to decrease. The curve for V_dep = 6 V even shows the lowest response to temperature changes, with the smallest sensor voltage across the entire temperature range. This decrease may be caused by the formation of a thick or rough ~~metal~~ Ni layer, which inhibits the conversion of temperature signals into ~~electrical~~ voltage. However, the sensor still shows a high R^2 value of 0.96, indicating stable responses and high accuracy [24], [25]. For further analysis, ~~only two sensors will be considered: the ones fabricated at deposition voltages of 4.5 V and 6.0 V.~~ only sensors with an R^2 value greater than 0.95 will be considered, as this indicates a significant influence of temperature on the sensor's voltage. Among the four sensors, two meet this criterion: the sensors with V_dep=4.5V and V_dep=6V.

Sensor Sensitivity

Figure 5 shows the sensitivity of two Cu/Ni coil sensors produced by electroplating at deposition voltages of 4.5 volts and 6.0 volts. Both sensors show a negative correlation between temperature and sensitivity: the lower the temperature, the higher the sensitivity.

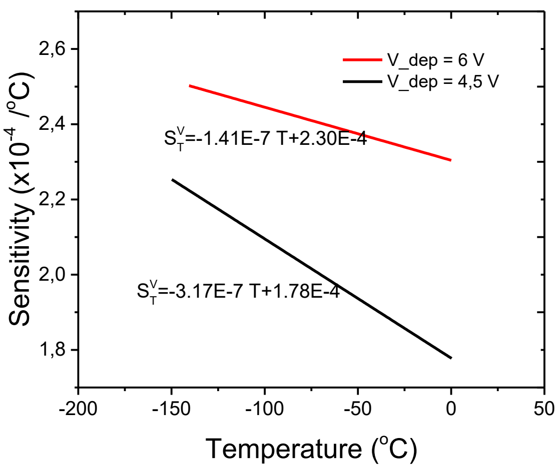

FIGURE 5. Sensitivity of two Cu/Ni coil sensors ~~produced by electroplating at deposition voltages of 4.5 volts and 6.0 volts~~

The sensor with V_dep = 4.5 V has a steeper slope, meaning it is more sensitive to temperature changes compared to the sensor with V_dep = 6.0 V. At 0°C, the sensor with V_dep = 6.0 V exhibits higher sensitivity compared to the 4.5 V sensor. However, ~~since the sensitivity decrease of the 4.5 V sensor is more pronounced, at lower temperatures, the difference may reduce or even reverse, depending on the measured temperature. Therefore, the 6.0 V sensor is more stable as it does not change significantly with temperature, while the 4.5 V sensor is more sensitive to temperature changes, although its sensitivity at 0°C is lower. As a result,~~ due to the sharper decrease in sensitivity at V_dep=4.5V, the difference between the two sensors become smaller, or even reverses, at lower temperatures depending on the specific temperature appointed. Therefore, the 4.5 V sensor is more suitable for measuring dynamic temperatures, while the 6.0 V one is more appropriate for measuring stable temperatures [26], [27], [22],[21].wab reviewer 2:

Commented [MT9]: Menjawab reviewer 2: • Diskusi hasil kadang berulang. Ringkas narasi yang menjelaskan grafik agar fokus pada interpretasi data.
Sudah diperbaiki, demikian pula untuk diskusi lainnya. Ulasan gambar sudah diperbaiki lebih berbasis data.

Hysteresis Loss

Based on observations of the hysteresis loop area as shown in Fig. 4, it can be concluded that the increase in electrode voltage during the sensor fabrication ~~contributes to~~ process affects the reduction of hysteresis losses. The sensor fabricated at V_dep = 6.0V ~~shows~~ exhibited a smaller hysteresis ~~characteristics~~ loop area compared to the ~~4.5~~

~~V deposition sensor~~ sensor at V_dep=4.5V ~~making it more suitable for temperature measurement applications that require high accuracy and long-term stability~~ [28],[29]..

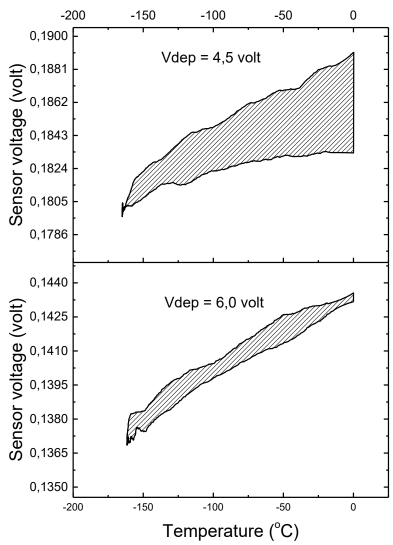

FIGURE 6. The hysteresis curve ~~losses~~ of two Cu/Ni coil sensors for calculating hysteresis losses ~~produced by electroplating at deposition voltages of 4.5 volts and 6.0 volts~~

For the V_dep = 4.5V sensor, the hysteresis area appeared larger, with the sensor output voltage ranging from 0.1791 V to 0.1895 V, and a large hysteresis loss of 0.0052 V. This indicates that, at the same temperature, the sensor voltage differs between the increasing temperature from -160°C to 0°C and the reverse tempereature. This leads to a larger voltage deviation [27,30]. In contrast, for the Vdep=6.0V sensor, the hysteresis area was narrower, with a voltage range of 0.1355 V to 0.1445 V and a small hysteresis loss of 0.0023 V. This suggests that, at the same temperature, the sensor voltage was almost identical between the increasing temperature from -160°C to 0°C and vice versa [31,[32]. This lead to a smaller voltage deviation [26].

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~~In the hysteresis curve for the 4.5 V deposition sensor, the area of hysteresis, shown by the shaded region between the heating and cooling curves, is relatively wide. The output voltage of the sensor ranges from 0.1791 V to 0.1895 V, with a significant hysteresis loss of 0.0052 V. This indicates that this sensor has a high hysteresis loss, which could reduce the accuracy of temperature readings and increase measurement uncertainty [27],[30]. In contrast, for the 6.0 V deposition sensor, the hysteresis area appears narrower, with a voltage range from 0.1355 V to 0.1445 V and a hysteresis loss of 0.0023 V. This demonstrates that the sensor's response to the heating and cooling cycles is~~

~~more consistent, with smaller voltage deviations at the same temperature [31],[32]. Therefore, hysteresis loss in this sensor is lower, indicating better stability and reliability in detecting temperature [26].~~

Comparison of R/R_0 for Samples against Pt-100

Figure 7 presents the data fitting results using Equation (4) for Cu/Ni coils fabricated at deposition voltages of 4.5 V and 6.0 V. For comparison, three reference materials - Ag, Cu, and Pt-100 - were included. The fitting constants obtained for each material are summarized in Table 1. These constants provide insight into the sensitivity and linearity of each material's response to temperature changes, as well as explain highlighting the performance differences between the electroplated Cu/Ni sensors and the reference materials.

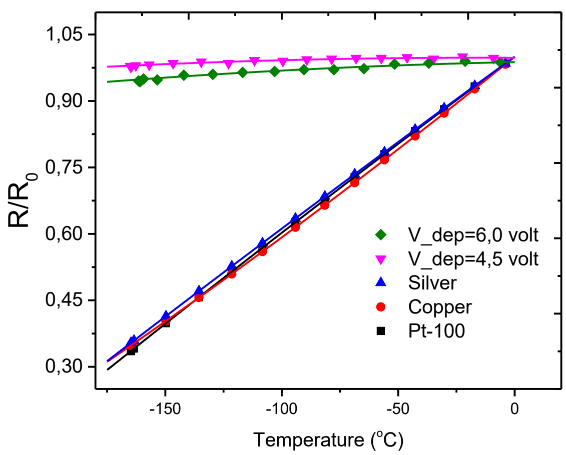

FIGURE 7. ~~The hysteresis losses of two Cu/Ni coil sensors produced by electroplating at deposition voltages of 4.5 volts and 6.0 volts.~~ The comparison of R/R_0 between the two sensors of Cu/Ni coil and the reference material Cu, Ag, and Pt-100.

TABLE 1. Fitting Constants for ~~Deposition~~ Samples at V_dep = 4.5 V, 6.0 V, Silver, Gold, and Pt-100.

Parameter	V_dep = 4,5 V	V_dep = 6,0 V	Pt-100	Silver (Ag)	Gold (Au)
A	9,33E-05	5,99E-04	3,91E-3	3.821E−3	3.76E−3
B	4,11E-07	3,86E-06	-5,78E-07	−6.01E−7	−5.88E−7
C	-1,39E-11	-5,14E-11	-4,18E-12	very limited data	very limited data

The Silver, Copper and Pt-100 sensor is highly sensitive and linear as shown in Fig. 7, making it an ideal temperature reference standard. The sensor with V_dep = 4.5 V has a relatively flat curve, with R/R_0 values ranging

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Sudah ditambah menjadi Ag, Cu, dan Pt

from 0.95 to 1.01 throughout the temperature range. In comparison to the three reference materials, the resistance change with temperature is minimal, that is 9.33E-5 (from A constant), indicating lower sensitivity. The sensor with V_dep = 6.0 V also has a relatively flat curve, though slightly below the 4.5 V curve, with R/R_0 values ranging from 0.92 to 1.0. Compared to the three reference materials, the initial resistance slightly decreases as the voltage increases, and the temperature sensitivity remains low that is 5.99E-04 [33],[34]. Increasing the voltage (from 4.5 V to 6.0 V) does not significantly improve sensitivity compared to the three reference materials and even tends to reduce signal stability.

From the value of constant B, which determines the degree of deviation of the curve from its linear state as a measure of sensor stability, it is observed that the B value for the V_dep 4.5 V sensor is on the same order of magnitude with the B values of the three reference materials, that is 10^{-7} which is the smallest numerical value 4.11E-7. Therefore, the sensor with V_dep 4.5 V is the most stable in responding to temperature changes compared to the others [35]. Meanwhile, the sensor with V_dep 6.0 V has the largest B value, 3.86E-6, indicating that this sensor is unstable in responding to temperature changes [36].

Table 2 presents a summary of the analysis of the Cu/Ni sensors at V_dep 4.5 V and 6.0 V. The final column shows a comparison with standard materials, namely Ag, Cu, and Pt-100. Although the sensors have not yet reached optimal performance at low temperatures, this study provides valuable insight into their positioning relative to commercial sensors, allowing for improvements in future research.

TABLE 2. Performance Characteristics of Cu/Ni Sensors at Different Deposition Voltages Compared with Ag, Cu, and Pt-100.

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Deposition Voltage	Response Time	Voltage Range	Temperature Response Consistency (R^2 of V–T Curve)	Sensitivity and Sensitivity Change	Hysteresis Loss	Comparison with R/R_0 of Ag, Cu, and Pt-100
0 V	Fast	Wide, with moderate noise	Poor	-	-	-
4.5 V	Moderately slow	Wide, slightly noisy	Excellent	High sensitivity, rapidly changing	Large, resulting in reduced accuracy	Less sensitive, most stable
6.0 V	Slow	Narrow, minimal noise	Good	High sensitivity, slowly changing	Small, resulting in higher accuracy	Less sensitiv, less stable
7.5 V	Moderately slow	Wide, slightly noisy	Poor	-	-	-

CONCLUSION

1. The electroplating technique has been effectively utilized to coat copper wire with nickel at different electrode voltages (0–7.5 V), producing a Cu/Ni temperature sensor that reacts to changes in cryogenic temperatures.
2. The sensor with a 4.5 V electrode voltage exhibited the highest sensitivity to temperature changes with good linearity ($R^2 = 0.96$), making it suitable for high-temperature dynamic applications, meanwhile the

sensor with a 6.0 V electrode voltage demonstrated the best signal stability with the lowest hysteresis loss (0.0023 V), making it more suitable for static and long-term temperature monitoring applications.

3. Although the performance of the Cu/Ni sensor has not yet matched the sensitivity of the commercial Ag, Cu, and Pt-100 sensors, the curve fitting results indicate that this sensor holds potential as a low-cost alternative with high design flexibility.

PRACTICAL IMPLICATIONS

The development of Cu/Ni wire-based cryogenic temperature sensors will have a significant impact across various fields. In cryo-preservation, the sensor will enhance the accuracy of temperature monitoring, ensuring that cells, tissues, or biological materials remain viable during the freezing process. Similarly, in LNG storage, it will improve safety in the management and transportation of LNG. In aerospace, the use of cryogenic temperature sensors will play a crucial role in controlling avionics systems, as temperatures can vary drastically outside of Earth's atmosphere.

FUTURE DEVELOPMENT PLANS

Future development will focus on improving the sensitivity and performance of the sensor. One approach will involve simulating deposition parameters such as electrolyte temperature, electrode distance, solution concentration, and the use of a magnetic field. Then, material combinations such as NiFe metal alloys will be explored to enhance the sensor's responsiveness at extremely low temperatures. Additionally, sensor protection will be implemented to increase resistance to harsh environmental conditions, such as corrosion and mechanical damage. Finally, efforts will be made to expand the application of these sensors across various industrial sectors, including cryo-preservation, LNG storage, and aerospace

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ACKNOWLEDGMENT

The author would like to express sincere gratitude to LPPM for providing research funding under contract number: PT-038/SP3/LPPM-UAD/XI/2024.

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