Investigation on Performance of Cu/Ni Film as Low Temperature Sensor

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Abstract. This research has investigated the effect of deposition time on the performance of Cu/Ni thin film as low temperature sensor. The sample was carried out by using electroplating technique on various deposition times from 1–5 minute. The liquid nitrogen was used as low temperature medium which the temperature was regulated from 0°C down to -200°C and vice versa. All Cu/Ni sensors perform a good response on the temperature change with variation of the output voltage range, time constants, sensitivity, and hysteresis losses. The Cu/Ni film produced during 1 minute deposition is the most sensitive sensor with sensitivity of (1.25 ± 0.01) mV/°C, but rather slow in responding temperature change and rather less stable voltage compared with the Cu/Ni film produced in 4 minute deposition. Unfortunately, the 4 minute sample is less sensitive in responding temperature change, that is (1.00 ± 0.01) mV/°C. We also found that all sensors have various hysteresis losses. The Cu/Ni film produced in 3 minute deposition has the minimum hysteresis area that is (6.640 ± 0.005)V/°C.

Keywords: Cu/Ni thin film, low temperature sensor, time response, sensitivity, hysteresis losses

1. Introduction

Currently the low temperature sensor is urgently needed in various fields such as in agriculture for food preservation, in medical field for organ preservation, and in animal husbandry field for preservation of animal sperm which will be used for artificial insemination [1-3]. All of that, requires a low temperature storage medium below -150°C. Therefore, a thermometer that can monitor the temperature of the medium at any time is needed. The most often used thermometers to measure low temperatures are gas thermometer, helium vapor pressure thermometer, Coulomb blockade, RTD, and p-n junction [4].

Nevertheless, making a temperature sensor below -150°C (cryogenic temperature) is not easy because the electrical and thermal properties of the material at this temperature are most non linear [4], so that the response of sensor acting at this temperature is also non linear and individual [5]. One of sensor materials that has the potential to be used as a low temperature sensor is CuNi alloy and Cu/Ni film [6]. The thin film shape is the main consideration because the electrical properties are quite different from the bulk. This is something that many researchers called as the size effect. The
use of Ni combined with Cu or coated on Cu is to increase the sensitivity of the sensor, because Ni has a higher resistivity (7.3 μΩcm) than Cu (1.7 μΩcm) [4].

In the previous work, we have done the study on the quality of Cu/Ni film as low temperature sensor materials prepared by electroplating on the various deposition time [7]. From the microstructure characterization with XRD it was found that all samples had a crystalline structure. Deposition time can affect the diffraction angle, shifted left or right, so that the interplanar spacing (d-spacing) changes. In the direction of (111) the smallest d-spacing corresponds to a sample of 3 minute deposition of 0.855Å. From the SEM photo it appears that the deposition time influences the size of Ni particle, the longer the deposition time the greater the particle size. The largest Ni particle size is in accordance with the sample produced in 5 minute deposition, that is 1.38 Å. This value is almost 4 times the grain size of the sample produced in a 2 minute deposition. From the sheet resistivity test, it is obtained that sheet resistivity of all samples are above sheet resistivity of Cu and the longer the deposition time the sheet resistivity decreases.

From these results, the study is continued on the calibration of the samples as low temperature sensors ranging from 0 down to -200°C. To calibrate the Cu/Ni sensor we use the thermocouple TCA-BTA which has range of temperature measurement from -200°C to 140°C. From the calibration we can obtain information regarding sensor sensitivity. Besides this, we also investigate the response times [8], stability of output voltage, and hysteresis losses. These four parameters are important parameters for the sensors.

2. Experimental method

2.1. Materials

The temperature sensor used as object in this research is the Cu/Ni films resulted from electroplating technique with deposition parameters as specified in Table 1. The experimental devices are arranged according to design shown in Fig.1. In the sensor calibration, 3 liters liquid nitrogen as low temperature medium is inserted into the flask that has a volume of 5 liters. Temperature of medium is measured using Cu/Ni sensor by immersing the sensor into the flask slowly at an average speed of 0.17 cm/s to the bottom of flask about 50 cm depth. With this speed, the decreasing temperature data from time to time gradually can be recorded properly.

| Cathode     | Cu       |
|-------------|----------|
| Anode       | Ni       |
| Electrodes distance | 4 cm     |
| Electrolyte | H₃BO₃(7.5 gr), NiSO₄(75 gr), NiCl₂(10 gr), and H₂O (250 ml). |
| Electrolyte temperature | 60°C     |
| Current density | 0.07 A/mm² |
| Deposition time | 1-5 minute |
| Estimated Thickness of Ni film | (10.3 – 81.5) nm |

Temperature measurement using Cu/Ni sensors cannot directly obtain the temperature quantity, but in the potential difference between the two ends of the sensor. Potential differences occur because of changes in resistivity in the Cu/Ni sensor as a result of changes in medium temperature [9-12]. Therefore, it is important to ensure that the measured voltage is pure from the sensor. To ensure the potential difference at the ends of the sensor is really from the sensor not included the voltage from the wire connected at the two ends of the sensors, the sensor is connected to the 4-WCB (Four Wire Configuration Bridge) transducer. To enlarge the output voltage (i.e. in order of millivolts), the voltage is amplified using Op-Amp up to 100 times more so that the output voltage is able to be
acquired with a VP-BTA voltage probe sensor that has range 0 – 5 volts.

![Block diagram of research](image)

**Figure 1.** Block diagram of research.

Furthermore, the voltage probe from the Cu/Ni sensor and the thermocouple probe are connected to the LabQuest Mini transducer and then from the transducer to the computer. The process of voltage and temperature data logging can be done coincident with the help of software loggerpro 3.8. Sampling rate is set to 2 data/s for 5 minute.

The next step is inserting Cu/Ni sensors into a flask together with the TCA-BTA thermocouple. Here, thermocouple is used to calibrate Cu/Ni sensors. According to data catalog this thermocouple has the ability to measure temperatures from -200°C to 1400°C, and for specific range temperature measurement, i.e. -200°C to 0°C it has a precision of ±5°C. When the sensor is still outside the flask, the sensor measures the room temperature. Since the sensor starts to enter the flask, the sensor measures the temperature of the medium which gradually drops from 0°C down to -200°C. The temperature difference between the top flask and the bottom one is due to the top of flask containing nitrogen gas so that the temperature is higher than that at the bottom containing liquid nitrogen. As revealed by Kar and Sharma, nitrogen starts to melt at -196°C [8-9], while the bottom of the flask contains liquid nitrogen, the temperature reaches -200°C.

After the temperature of -200°C is reached, the sensor is pulled up slowly until it is outside the flask. The logged data is displayed in two versions that are numeric and graphic. The numerical data contains the arrays of time data ($t_i$), sensor voltage ($V_i$) and temperature of thermocouple ($T_i$), while the graphical data contains the curve of $V$-t from Cu/Ni sensor and $T$-t from thermocouple. Data is then analyzed to obtain a range of sensor voltages, response times, stability, sensitivities, and hysteresis losses.

### 2.2. Procedure of Data Analysis

1) **Voltage range.** The temperature to be measured has the range of 0°C down to -200°C. The measured temperature is expressed in voltage quantities. In fact the magnitude of the output voltage of each sensor varies in the range of temperatures between 20°C to 200°C. Voltage range of each sensor is obtained from the output voltage difference when the sensor will be used to measure the two temperatures that are 20°C and -200°C. Range voltage is a parameter that contributes to the resolution of sensor. The greater the size of the voltage range leads to the greater resolution.

2) **Accuracy of Sensor.** The accuracy of sensor is shown through a clear and consistent relationship between output voltage and temperature. Some theories revealed that the relationship between resistivity and temperature is linear, polynomial order-3, or even any order polynomial. However, the simplest form is linear [13-14]. Shortly speaking, the most important thing is the consistency of the relationship between temperature and resistivity. Because of the resistivity here is
represented by the voltage, the relationship between resistivity and temperature is substituted by the voltage and temperature $V(T)$.

3) Sensitivity and stability of sensor. The description of the sensitivity level of sensor is done by matching the sensor voltage data ($V$) to temperature ($T$) in the temperature range -140°C to 0°C. The voltage variation of the sensor describes the variation in sensor resistance because the temperature of the medium changes when it is electrified.

As shown in the Matthiessen formula for pure metals [15-16], the total resistivity of the sensor follows the PTC (Positive Temperature Coefficient) pattern. This resistivity is contributed by two factors, i.e.: first, from electron scattering when collides to the lattice vibration, and second, by scattering electrons due to collision with the residue, that consists of crystal defects and impurities in the material. The first type is dependent temperature, while the second type is independent one.

From the $V$-$T$ curve, the most sensitive sensors have the largest slope. Furthermore, the stability of the sensor is shown by the precision level of the sensor in measuring temperature. Precision level can be seen from the magnitude of the data deviation ($V_i, T_i$) to the $V$-$T$ curve. Overall, it can be represented by the standard deviation. Then, the sensor that has the smallest standard deviation will indicate that the sensor is the most accurate in appointing the measurement temperature, or the most stable.

4) Response time of sensor. To determine the response time of sensor, the activity is divided into two parts, the first is when the temperature decreases from -20°C down to -200°C and the second is when temperature rises from -200°C to -20°C. This division is important by considering that the response time of sensor to the decreasing temperature is different from the response time for increasing one, so it needs an explanation separately. The upper limit of temperature is limited to -20°C because of a consideration that in the future the application of sensor will be dedicated more specifically for cryogenic sensors. As an example in the animal husbandry, the upper temperature limit for storing cow cement is -100°C. So that temperatures above -40°C are less relevant. Then, response time of sensor is obtained by drawing a graph of voltage ($V_i$) with respect to time ($t_i$). The most suitable equation to express the relationship between $V_i$ data and $t_i$ is exponential, i.e.:

$$ V = m_1 e^{-m_2 t} + m_3 $$

where $V$ is voltage, $m_1$, $m_2$ and $m_3$ are fitting constants. The $m_2$ is a time constant which is a measure of the sensor’s speed in response to the temperature. The increasing $m_2$ leads to the sensor faster in responding the medium temperature.

5) Hysteresis losses. An error in the sensor is ordinary thing. There is no perfect sensor even for commercial equipment produced by the same factory even was set to the same parameters. The results of the reading can be slightly different from the true value. May be this is relating with selection of the quality of the dc voltage source, the quality of the circuit, properly connection between electronic components, and the compatibility between the current from DC power and the ability of sensor to accept and flowing the current [17–21].

A good temperature sensor is a sensor that can exhibit the same temperature even used at other times. Hysteresis loss in here is a loss arising due to the difference voltage, if a sensor is used to measure the same temperature. If the voltage difference occurs when the medium temperature is decreased from -20°C down to -200°C and vice versa the hysteresis lop will be formed.

The hysteresis curve should be like a leaf, which is balanced between the left and right. But in this research-due to technical reasoning- the thermocouple is only able to measure the low temperatures down to -140°C, meanwhile the Cu/Ni sensor is able to continue its measurements up to the temperature of liquid nitrogen (-200°C). Then a part of the hysteresis loop from -140°C to -200°C is not appeared (see Fig. 2).
The hysteresis loss is expressed by the shaded area. The area is computationally determined by following the trapezoidal formula i.e.

$$A = \frac{h}{2} \left( y_0 + y_n + 2 \sum_{i=1}^{n-1} y_i \right)$$

(2)

where $h$ is the distance between temperature $T_i$ that is about 0.55 min, and $y$ is voltage $V$.

3. Results and discussion

3.1. Output Voltage in Measuring Liquid Nitrogen

In Fig. 3, as an example, the measurement of liquid nitrogen temperature done by thermocouples and by Cu/Ni sensor is displayed together. The Cu/Ni sensor was produced from 5 minute deposition. The data logging was set for 5 minute with the sampling rate of 2 data/second. On the left side, the time, temperature and potential data are displayed numerically, while on the right side output voltage and temperature against the time is displayed graphically.

From the figure, one can see the minimum temperature from thermocouples that can be reached that is -140°C, which is shown by horizontal lines (the bottom fig.), while Cu/Ni sensors
still continue to decrease until they reach the temperature of -200°C. Then, with the same way, the data collection of liquid nitrogen temperature is carried out for all sensors together with the thermocouple. After processing data, the results are displayed together in the V-t curve as shown in Figure 4.

![V-t Curve](image)

**Figure 4.** The curves of voltage from Cu/Ni sensors resulted from deposition Ni at variations of deposition time 1–5 minute in measuring temperature of liquid nitrogen.

All sensors exhibit their ability to respond the changes on temperature of liquid nitrogen (Fig. 4). The minimum temperature that can be measured by thermocouples is -140°C while Cu/Ni sensors are still able to continue to measure temperature to -200°C.

Unfortunately, the ripple is found to still accompanies the output voltage with different amplitude and position. On relatively high temperature, above -40°C the ripple looks more fluctuating than on below -40°C. This ripple has strong relation to the fluency of electric current flowing on the surface of sensor. The ripple occurs due to the poor quality on connection between sensors and cables, cables and electronic components, and the incompatibility between the electric current flowing in sensor and the size of sensor.

![Output Voltage vs Deposition Time](image)

**Figure 5.** The range of output voltage of Cu/Ni sensors when used to measure temperatures from 20°C – -200°C. (a) for decreasing temperature, (b) for increasing temperature.

From the investigation on the range of output voltage of Cu/Ni sensors as shown in Fig. 5, the values vary from 0.10 V to 0.25 V. The largest range is in accordance to Cu/Ni sensors produced from 1 minute deposition that is 0.25 volt. The range of voltage in temperature sensor has important role due to the relation to sensitivity of sensor. Sensor that has a greater voltage range can respond a
wider temperature range so it is more accurate in appointing the temperature because the little change in temperature has been able to produce the change of voltage. Thus, the Cu/Ni sensor obtained from deposition for 1 minute has the largest sensitivity compared to the sensor resulted from another deposition time.

3.2. Response Time of Cu/Ni sensors

In Fig. 6 it can be reported the time response of sensor in sensing liquid nitrogen from 20°C to -200°C and vice versa. For the temperature decrease from 20°C to -200°C the curve (Ti, ti) of the thermocouple almost coincides with the curve (Vi, ti) of Cu/Ni sensor.

![Figure 6. Data fitting of voltage-time to determine the time constant. (a) decreasing temperature of N2, (b) rising temperature of N2.](image)

This shows that Cu/Ni sensors can respond to temperature changes as well as thermocouples. However, this becomes different for the rising temperature from -200°C to 20°C, the position of the Cu/Ni sensor curve is rather more right than the position of thermocouple curve. This indicates that Cu/Ni sensors experience slight delays in responding temperature changes if it is compared to thermocouples. Indeed, for thin layer-based temperature sensors - as said by Anand - the average response time is slower than that for thermocouples [22]. However, the advantage of Cu/Ni sensor is on the ability to measure the low temperature up to -200°C lower than the low temperature able to be reached by the thermocouples. To determine the response time of each sensor the fitting of data (Vi, ti) is performed for the decreasing temperature and also for the rising temperature according to the exponential function according to (1). The result is displayed on Fig. 6. The value of the time constant (m2) is tabulated in Table 2 column 2 for decreasing nitrogen temperature and column 4 for increasing nitrogen temperature.

| Depositon Time (min) | Time constant for decreasing temperature of N2 (min⁻¹) | Relative error | Time constant for increasing temperature of N2 (min⁻¹) | Relative error | Time to achieve Temp. of -200°C (min.) |
|----------------------|------------------------------------------------------|----------------|------------------------------------------------------|----------------|---------------------------------------|
| 1                    | 6.63 ± 0.37                                          | 5.6%           | 1.77 ± 0.03                                          | 1.7%           | 0.93                                  |
| 2                    | 3.28 ± 0.30                                          | 9.1%           | 1.93 ± 0.15                                          | 7.8%           | 0.66                                  |
| 3                    | 1.77 ± 0.11                                          | 6.2%           | 1.39 ± 0.02                                          | 1.4%           | 1.08                                  |
| 4                    | 7.94 ± 0.43                                          | 5.4%           | 1.50 ± 0.01                                          | 0.7%           | 1.08                                  |
| 5                    | 6.42 ± 0.34                                          | 5.3%           | 1.80 ± 0.02                                          | 1.1%           | 1.08                                  |
Due to the differences in the time constants, the time needed for the sensor to reach a temperature of \(-200^\circ C\) also varies. For decreasing temperature of \(N_2\), sensor Cu/Ni resulted from 4 minute deposition time is the fastest sensor in responding to the changes of temperature. This sensor has the time constant of \((7.94 \pm 0.43)/\text{minute}\). Meanwhile for increasing temperature of \(N_2\), the sensor produced from 2 minute deposition time is the fastest in response to temperature changes and also the fastest to reach a temperature of \(-200^\circ C\) that are 1.93/minute and 0.66 minute respectively.

From previous work [7], regarding to XRD analysis it is obtained that the sensor resulted from 2 minute of Ni deposition has the highest diffracted beam intensity compared to other samples so that it is the most regular crystal structure. But from analysis of crystal size by using Scherrer formula [23,24], that sensor has the smallest particle size i.e. 0.38Å. The small particle size is thought due to the thickness of the Ni layer that relatively thin so that the deposit is still dominated by diffusion layer. From the formula of the relationship between the thickness of the layer \(d\) (µm) and the deposition time \(t\) (minute) as has been obtained, i.e. \(d = 1.28 \times 10^{-5} t - 4.43 \times 10^{-7} \) (m), the thickness of Ni produced in 2 minute deposition is 0.25 µm while the thickness for that in 4 minute deposition is 0.51 µm [7].

As known, a good low temperature sensor is an alloy between Cu and Ni to form CuNi [25]. In electroplating this can not be carried out because the Ni layer attached to the surface of Cu to produce a Cu/Ni layer even though at the interface there are Ni atoms which diffuse into the Cu surface to form diffusion layer. This part play an important role in determining the quality of temperature sensor. The diffusion process can also move atoms, molecules, and clusters of atoms on the surface of the material so that mutual diffusion or interdiffusion is possible to be occured. Therefore, diffusion clearly affects the morphology of the layer.

The diffusion of Ni atoms into the Cu layer is relatively easy because the size of both atoms is almost the same, which is 0.1278Å for Cu and 0.1246Å for Ni. The diffusion process only occurs in a few moments until the crystal defects in Cu are filled, and after that Ni atoms continue the coating process to produce a continuous layer to form Stranski Kastranov type [26]. The thickness of effective diffusion layer formation according to Fellner is about 3 µm [27]. When the layer is more continuous, the current density that passes through it increases [28]. Similarly, by considering that Cu is a good conductor and low resistivity \((1.7 \times 10^{-8} \, \Omega \text{m})\) while Ni has a high resistivity \((7.0 \times 10^{-8} \, \Omega \text{m})\), if Cu and Ni are combined the resistivity of Cu will increase.

As in previous explanation, the presence of a ripple in the output voltage signal indicates that the electric current on the sensor is not yet stable. The level of stability of the output voltage signal can be seen in the relative error of the time constant (column 3 and 5, Table 2). The more stable output voltage signal is indicated by the small relative error. From this, for N2 temperature down Cu/Ni sensor resulted from 5 minute deposition is the most stable output voltage with a 5.3% relative error. However, for rising N2 temperature, Cu/Ni sensor resulted from 4 minute deposition is the most stable with relative error of 0.7%. Conversely, the samples produced from 2 minute deposition had the largest relative error both for decreasing and rising N2 temperature, that are 9.1% and 7.8%. This sensor is the most unstable voltage signal and not good if it will be used as temperature sensor.

### 3.3. Sensitivity of Sensor

Sensitivity is the most important quantity of sensor quality because the essence of study about sensors is to find materials which sensitive to the change in other quantities. The other quantities are complementary, although it is also very important. The relationship between sensor output voltage (V) and medium temperature (T) is displayed in Fig.7. To explain the sensitivity of the sensor, an analysis of the graphs of data fitting \((V_i, T_i)\) was carried out according to the linear regression. The result is a linear equation as shown in Table 2. From the value of the determination index R2 approaching 1 as shown in column 3, it indicates that all samples have a strong linear relationship between the output voltage and the temperature of N2. This is an advantage of this Cu/Ni sensors, by considering the difficulty of finding the cryogenic sensors that have a linear relation in both electrical
and thermal properties to the temperature, as revealed by Lebioda and Rymaszewsky [4] or Yeager and Courts [2].

Information about sensitivity levels of sensor can be investigated through the slope of graph. The slope of graph illustrates the change of the sensor voltage due to the changes in temperature of the medium. The larger slope of the curve the more sensitive the sensor. Sensitivity level of each sensor is shown in Table 2 column 4.

![Figure 7. Sensitivity of the sensor.](image)

**Table 3. Linear Equation between Sensor Output Voltage and Medium Temperature.**

| Deposition Time (minute) | Relationship between voltage and temperature (volt) | Determination Index, $R^2$ | Sensitivity (mV/°C) |
|--------------------------|-----------------------------------------------------|---------------------------|---------------------|
| 1                        | $V=0.0012 \ T + 0.6634$                            | 0.99                      | 1.26 ± 0.01         |
| 2                        | $V=0.0007 \ T + 0.7213$                            | 0.95                      | 0.74 ± 0.02         |
| 3                        | $V=0.0004 \ T + 0.5803$                            | 0.98                      | 0.43 ± 0.01         |
| 4                        | $V=0.0010 \ T + 0.6672$                            | 0.99                      | 1.00 ± 0.01         |
| 5                        | $V=0.0008 \ T + 0.6340$                            | 0.99                      | 0.76 ± 0.01         |

In general, all samples have shown a positive response to temperature changes of N$_2$ from -140°C to 0°C. Table 2 column 4 show that the sensitivity level is influenced by the deposition time. The sensitivity level of sensor ranges from 0.43 mV/°C to 1.25 mV/°C. This sensitivity is higher than that has been resulted by Yang for Cu/CuNi sensor to measure temperatures from 30°C to 200°C. The sensitivity is about 43.94 μV/°C to 46.49 μV/°C [29]. Furthermore, the highest sensitivity of sensor that Yang obtained is 46.49 μV/°C concerning to the sample as thick as of 0.5 μm. In this study, the deposition of Cu/Ni sensors within 1 minute is according to the thickness of 12.40 μm and has the highest sensitivity compared to other sensors, that is (1.25 ± 0.01) mV/°C.

This sample is interesting as the sensitive sensor and quite fast in responding to temperature changes especially for the decreasing medium temperature, with a time constant of (6.63 ± 0.37) /minute which is number 2 after the time constant for sensor produced in 4 minute deposition. Similarly, the time needed to reach a temperature of -200°C from 20°C is quite short, that is 0.66 minute. The next level of sensitivity is (1.00 ± 0.01) mV/°C that is in accordance with the sample produced from 4 minute deposition. This sample also has the highest time constant the decreasing medium temperature that is (7.94 ± 0.43)/minute for.
3.4. **Hysteresis Losses**

In completing information about the characteristics of Cu/Ni sensors, information about hysteresis loss was displayed in the form of hysteresis area, as pointed on Fig. 5. One of the characteristics of a good temperature sensor is having the smallest hysteresis area. For the ideal sensor the measured temperature of the medium in the decreasing temperature process is same to the temperature in increasing process. The hysteresis loss describes the loss due to inequality of sensor to measure the temperature of the medium at different times that are for decreasing and increasing temperatures. Hysteresis loss is also related to reproducibility.

According to Aydemir [30] and dan Fank [28] the existence of hysteresis is influenced by the structure of film. They also suggested for reducing hysteresis losses 1/2 up to 1/3 times that should be done by annealing the film at the certain temperature. In this study the measurement of temperature is done by Cu/Ni sensors, and the output in a voltage quantity.

Hysteresis loop is formed from depict \((V_i, T_i)\) data for decreasing temperature from \(20°C\) to \(-140°C\) connected continuously by the data for increasing temperature from \(-140°C\) to \(20°C\). In Fig. 8 the hysteresis curve of each sample is displayed. Here, a part of hysteresis loop on the left side is not present because the minimum temperature that is possible be measured by thermocouple is \(-140°C\), although the Cu/Ni sensor is still able continue measuring the medium temperature lower that is \(-200°C\). So the curve \(V-T\) below \(-140°C\) doesn’t exist. Therefore, the hysteresis loss is presented by the hysteresis area according to (2) not in percent hysteresis. From the figure it appears that all samples have a different hysteresis loss.

![Figure 8. Hysteresis loop of the voltagedemperature curve of the cu/ni sensor, resulted from deposition in a time variation.](image)

The smallest hysteresis is \((6.640 \pm 0.005) V°C\) corresponds to the Cu/Ni sensor from deposition of Ni within 3 minute. Meanwhile, the largest hysteresis loss is in accordance with the sensor resulted from 4 minute Ni deposition, that is \((20.653 \pm 0.005) V°C\).

Sensors that have a small hysteresis area will be more accurate if used to measure temperature at any time. Unfortunately, the hysteresis loop curve of all these sensors is less complete, that is for the section at temperature below \(-140 °C\) so that in this study we cannot conclude exactly which sensor that has the smallest hysteresis loss. At least the existence of these results has been able to provide an overview of the limitations of sensors in providing precision temperature measurements. As a consideration, from the previous work on study about microstructure of samples it was found that there was a tendency that the increase in deposition time made the arrangement of Ni crystals became irregular even though their thickness increased. The irregularity of the crystal arrangement is characterized by the decreasing intensity of the XRD diffraction peak. But d-spacing is getting closer...
even this sample has the smallest that is 1.2166Å. With the small d-spacing, it is expected that electric conduction will take easier both the decreasing and rising medium temperatures. It leads to the hysteresis area smaller, and then reducing the hysteresis losses.

![Graph showing the characteristic of Cu/Ni sensors on the various deposition time.](image)

**Figure 9.** Characteristic of Cu/Ni sensors on the various deposition time.

As a resume from the discussion and analysis that have been done, in Fig. 9, an illustration of the advantages and disadvantages of each sensor which consists of a range of voltage, time constant for decreasing and increasing temperatures, sensitivity of sensors, stability of sensor, and hysteresis losses is given. It is not easy to obtain a sensor produced by electroplating in a variation of the deposition time which has advantages on all sensor quality parameters. But the most important parameter here is sensor sensitivity, while other parameters role as contributing factors in complementing the main parameter. The Cu/Ni layer produced from 1 minute deposition is the most sensitive one compared to the other sensors but has the smallest voltage range, while the response time if used to measure the medium temperature which goes both decrease and increase is quite well. The second one is Cu/Ni sensor produced on 4 minute of Ni deposition. This sensor is most responsive to the decreasing medium temperature, sensitive, has stable voltage signal in both decreasing and increasing medium temperatures but the time constant is not so large for the increasing temperature so the time to reach the -200°C is rather slow compared with the sensor produced in 1 minute of Ni deposition. Unfortunately, both 1 minute and 4 minute sensors of Ni depositions have the large hysteresis losses. Furthermore, another sensor is not considered because of the weakness in the main quality parameter, that is sensitivity.

The sensor is stable enough compared to other sensors except the sensor resulted within 2 minute of Ni deposition. Similarly, the loss of hysteresis is still quite large. The Cu/Ni sensor resulted from 2 minute of Ni deposition has a sensitivity level below the Cu/Ni film sensor resulted from 1 minute deposition. The range of the output voltage of this sensor is not so large, and also the time constant for the decreasing medium temperature is less good, while the time constant for the rising medium temperature is quite good, the output voltage signal in response to temperature changes is stable enough, but this sensor has a large enough hysteresis loss.

Therefore, in this preliminary study, even though we have obtained deposition time which is capable to produce Cu/Ni sensors with high sensitivity, it still contains a further tasking in finding solutions to some deficiencies that accompany on these parameters of sensitivity. It is expected that the results of further research can overcome these deficiencies so that the Cu/Ni low temperature sensor which has more quality parameters can be found.

4. **Conclusion**

The plating of Ni on Cu substrate by varying the mass fraction of Ni in solution influences the thickness of Ni film, microstructure, and sensitivity of Cu/Ni as a low-temperature sensor. The
thickness of Ni is proportional to the electrolyte concentration. Analysis on resistivity obtained information that resistivity of Cu/Ni depends not only on the thickness of the Ni film but also by the regularity of the crystal and grain size. All samples can be used as low-temperature sensors to measure temperatures from 0°C to -140°C. Sensitivity is a linear relation to ambient temperature where S5 has the highest sensitivity that is 1.05×10⁻³ V/°C.

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