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Research Article

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Voltage-Dependent Copper Electrodeposition and Apparent Faradaic Efficiency in a Copper Sulfate Electroplating Cell

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Abstract

Electroplating is an electrochemical process in which metal ions are reduced onto a conductive surface; its practical usefulness is dependent on the amount of metal deposited and the efficiency of with which electrical charges produce the desired reactions. This study investigated how applied voltage affects copper electrodeposition and calculated Faradaic efficiency in a copper sulfate electroplating cell. Copper electrodeposition was conducted using a copper anode, nickel cathode, and 250 cm3 of 0.50 mol dm-3 aqueous copper (II) sulfate. The applied voltage varied from 1.00 V to 5.00 V, in 1.00 V increments, while electrolysis time (300 s), electrode spacing (2.0 cm), submerged electrode area, solution volume, and electrode preparation were held constant. The mean copper mass deposited had increased from the initial 0.020 g at 1.00 V to 0.050 g at 4.00; however, it then remained similar at 5.00 V within the measurement's precision. Under the idealized model used in this study, calculated Faradaic efficiency decreased from approximately 101% at 1.00 V to 47% at 5.00 V. The apparent efficiency above 100% at the lowest voltage is attributed to the small, measured mass relative to balance resolution. These results are indicative that higher voltages can increase deposition rate but may reduce electrochemical efficiency because of side reactions, heating, polarization, and non-idealistic current behavior.

List of Abbreviations

FE	:	Faradaic efficiency
SD	:	Standard deviation
R2	:	Coefficient of determination
CuSO4	:	Copper(II) sulfate

Keywords: Copper Electroplating; Electrodeposition; Faradaic Efficiency; Copper Sulfate; Applied Voltage; Electrolysis

Introduction

Electroplating is an electrochemical process that uses an external electrical potential to deposit a thin metallic layer onto a conductive substrate. It is widely used to improve appearance, corrosion resistance, electrical properties, thickness, and surface performance of manufactured components [1,2]. In a simple copper electroplating system, copper metal is oxidized at the anode to form copper (II) ions, while copper (II) ions in solution are reduced at the cathode and deposit as solid copper.

The amount of metal deposited during electrolysis is commonly related to the total charge passed through the cell by Faraday's law of electrolysis [3]. For copper deposition, each copper (II) ion requires two electrons to form copper metal. Therefore, if current, time, molar mass, and Faraday's constant are known, the theoretical mass of copper deposited can be estimated. However, real electrochemical systems do not always convert all applied charge into the target product. Faradaic efficiency is therefore useful because it compares the experimentally obtained product with the amount predicted from charge transfer [4].

This investigation examined how applied voltage would affect the mass of copper electroplated and the calculated apparent Faradaic efficiency of a copper sulfate electroplating system. The faradaic efficiency extension was included because electroplating performance is not only dependent on deposition rate, but also on how effectively input contributes to the desired copped reduction reaction.

The original aim of this investigation was to determine how applied voltage affects the mass of copper electroplated under controlled resistance and time. For publication-style reporting,

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the central focus is extended to include Faradaic efficiency because efficiency is more relevant to industrial electroplating and process optimization than mass alone. The guiding research question is: How does applied voltage from 1.00 V to 5.00 V affect the mass of copper deposited and the calculated Faradaic efficiency during electrolysis of 0.50 mol dm-3 aqueous copper (II) sulfate under constant time, electrode spacing, submerged electrode area, solution volume, and electrode preparation?

It was hypothesized that increasing voltage would increase copper mass deposited because a higher applied potential should increase the current in the circuit under an ideal constant-resistance assumption. It was also expected that calculated Faradaic efficiency might decrease at higher voltages because practical electrochemical cells can deviate from ideal Ohmic behavior through heating, polarization, concentration gradients, side reactions, and rougher deposit formation.

Materials and Methods

Materials

Copper electrodeposition was carried out using a DC power supply (0-5 V), digital voltmeter (+/- 0.01 V), stopwatch (+/- 1 s), copper electrode as the anode, nickel strips of similar dimensions as cathodes, clamp stand with electrode holder, connecting wires with crocodile clips, a 250 cm3 beaker, filter paper or paper towels, distilled water, and 250 cm3 of 0.50 mol dm-3 CuSO4(aq). A digital balance with a resolution of +/- 0.01 g was used to measure cathode mass before and after electrolysis.

Experimental Design

The applied voltage was varied at five levels: 1.00, 2.00, 3.00, 4.00, and 5.00 V. Each voltage condition was repeated for three trials. Electrolysis time was held constant at 300 s for every trial. Electrode spacing was maintained at 2.0 cm using a ruler, and the depth of submersion was held constant by marking the same immersion line on each electrode. A single prepared batch of 0.50 mol dm-3 CuSO4(aq) was used to maintain a consistent electrolyte concentration and solution volume across trials.

Preliminary trials using smaller voltage increments produced mass changes that were difficult to distinguish using the available balance resolution. The final design therefore used 1.00 V increments. Preliminary trials also showed that the copper anode developed surface residue during electrolysis; therefore, the anode was rinsed and wiped between trials to maintain more consistent electrode surface conditions.

Procedure

Before each trial, the cathode was dried and weighed to obtain its initial mass. The copper anode and nickel cathode were clamped into the electrolyte at the marked immersion depth with 2.0 cm spacing. The positive terminal of the power supply was connected to the copper anode and the negative terminal to the nickel cathode. The selected voltage was set using the power supply and checked with a voltmeter. Electrolysis was carried out for 300 s. After electrolysis, the cathode was removed, rinsed with distilled water, dried, and reweighed. The mass of copper deposited was calculated as the final cathode mass minus the initial cathode mass. The copper anode was rinsed and dried before the next trial.

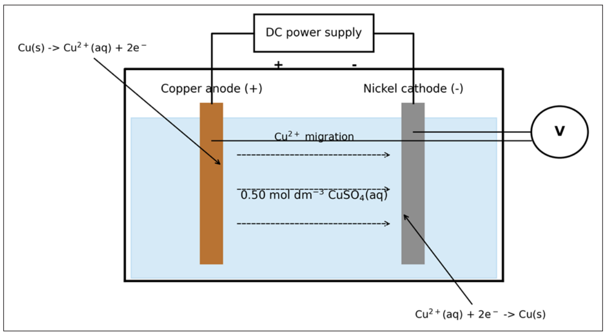

Figure 1: Schematic of the copper electroplating cell used in the investigation. The schematic is original and replaces the textbook-style diagram used in the school-lab version of the report.

Safety and Environmental Considerations

Copper (II) sulfate solution can irritate skin and eyes and is harmful if ingested. Gloves and safety goggles were used during solution handling, and direct contact with the electrolyte was avoided. The DC power supply was used only on a dry bench with secure electrical connections, and the circuit was switched off before electrode adjustments. Copper-containing waste was not disposed of in the sink; it was collected for appropriate heavy-metal waste disposal according to laboratory safety procedures.

Theory and Calculations

At the copper anode, oxidation occurs: Cu(s) → Cu2+(aq) + 2e-. At the nickel cathode, copper (II) ions are reduced and plated as solid copper: Cu2+(aq) + 2e- → Cu(s).

The theoretical mass of copper deposited can be estimated from Faraday's law:

$$m = \frac{QM}{nF}$$

where m is mass deposited, Q is total charge passed, M is the molar mass of copper, n is the number of electrons transferred per copper (II) ion, and F is Faraday's constant. Since Q = It, and the original model estimated current using I = V/R, the idealized theoretical mass becomes:

$$m_{theory} = V \cdot \left[\frac{tM}{RnF} \right]$$

For the calculations in this study, t = 300 s, M = 63.546 g mol^{-1}, n = 2, F = 96485 C mol^{-1}, and the effective resistance assumption from the original model was R = 5.00 ohm. Faradaic efficiency was calculated as:

$$FE(\%) = \frac{m_{\exp}}{m_{theory}} \times 100$$

This model assumes constant effective resistance and 100% conversion of charge into copper deposition. In practice, electrochemical cells may deviate from this idealization because current can change during electrolysis as temperature, electrode surface condition, concentration gradients, polarization, bubble formation, and deposit morphology change [3,5]. Therefore, the calculated theoretical masses are best interpreted as idealized reference values rather than exact expected values.

Results

During electrolysis, the nickel cathode gained an orange copper coating up to the line of submersion. At lower voltages from 1.00 V to 3.00 V, the deposit appeared smoother, lighter in colour, and less dense. At higher voltages, particularly 4.00 V and 5.00 V, the copper layer appeared darker and rougher, suggesting more irregular deposition. The copper (II) sulfate solution remained blue throughout the trials, though slight fading near the cathode was observed.

Table 1: Raw Cathode Mass Measurements and Calculated Mass Change After 300S of Electrolysis

Voltage / V	Trial	Time / s	Initial cathode mass / g	Final cathode mass / g	Mass change / g
1.00	1	300	1.08	1.10	0.02
1.00	2	300	1.05	1.07	0.02
1.00	3	300	1.06	1.08	0.02
2.00	1	300	1.06	1.09	0.03
2.00	2	300	1.06	1.09	0.03
2.00	3	300	1.05	1.08	0.03
3.00	1	300	1.04	1.07	0.03
3.00	2	300	1.04	1.08	0.04
3.00	3	300	1.05	1.09	0.04
4.00	1	300	1.06	1.11	0.05
4.00	2	300	1.05	1.10	0.05
4.00	3	300	1.06	1.11	0.05
5.00	1	300	1.08	1.13	0.05
5.00	2	300	1.07	1.12	0.05
5.00	3	300	1.07	1.11	0.04

Table 2: Processed Data Showing Mean Experimental Mass, Standard Deviation, Idealized Theoretical Mass, And Calculated Faradaic Efficiency

Voltage / V	Mean mass deposited / g	SD / g	Theoretical mass / g	Faradaic efficiency / %	Main observation
1.00	0.0200	0.0000	0.0198	101.2	0.02
2.00	0.0300	0.0000	0.0395	75.9	0.02
3.00	0.0367	0.0058	0.0593	61.9	0.02
4.00	0.0500	0.0000	0.0790	63.3	0.03
5.00	0.0467	0.0058	0.0988	47.2	0.03

The balance resolution was +/- 0.01 g for each mass measurement, giving a propagated single-trial mass-change resolution uncertainty of approximately +/- 0.02 g. Because several measured changes were close to this value, the numerical efficiency values should be interpreted cautiously, especially at 1.00 V.

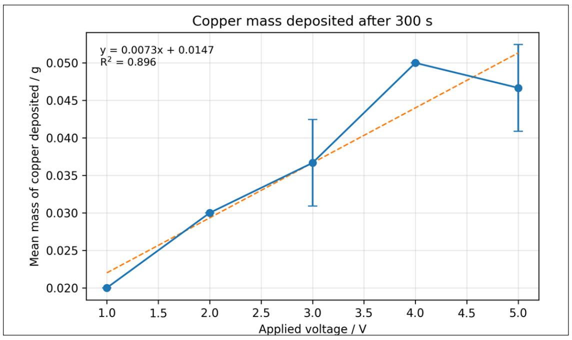

Figure 2: Mean mass of copper deposited as a function of applied voltage. Error bars represent the standard deviation of three trials. Linear regression gave y = 0.0073x + 0.0147, R2 = 0.896.

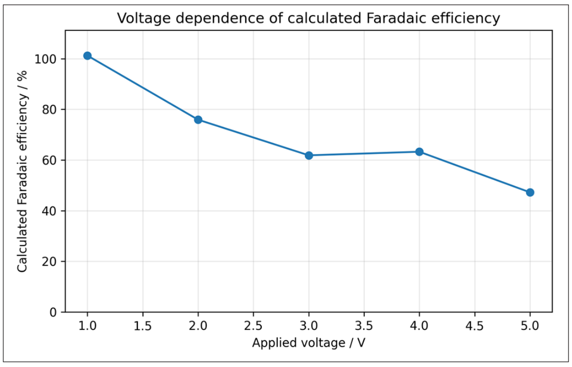

Figure 3: Calculated Faradaic efficiency as a function of applied voltage using the idealized constant-resistance model. The value slightly above 100% at 1.00 V reflects measurement resolution rather than true efficiency above unity.

Discussion

The results show that the mass of copper deposited generally increased with applied voltage. The mean mass increased from

0.020 g at 1.00 V to 0.050 g at 4.00 V. At 5.00 V, the mean mass was 0.0467 g, which is similar to the 4.00 V result within the measurement limitations of the available balance. Therefore, the data supports an overall positive relationship between applied voltage and deposited mass, but they do not support an unlimited linear increase across the full voltage range.

The regression of mean mass deposited against voltage produced a slope of 0.0073 g V-1 and an intercept of 0.0147 g, with R2 = 0.896. The non-zero intercept is not predicted by the idealized model and may be caused by balance resolution, incomplete drying of the cathode, small differences in electrode surface condition, or the limited number of trials. Because the individual mass changes were small, especially at lower voltage, small handling or drying differences could have a large relative effect.

The most important result is the decrease in calculated Faradaic efficiency as applied voltage increased. Based on the idealized theoretical model, calculated Faradaic efficiency decreased from approximately 101% at 1.00 V to 47% at 5.00 V. The 1.00 V value should not be interpreted as true efficiency greater than 100%; rather, it shows that the measured mass was so small that rounding and balance resolution had a major influence. At higher voltages, the decrease in calculated efficiency suggests that a smaller proportion of the applied electrical input was reflected in measured copper deposition.

Several mechanisms may explain the reduced efficiency at higher voltage. Higher applied voltage can increase overpotential and current density, which may promote side reactions such as water reduction and gas evolution. It can also increase Joule heating in the cell, change local ion concentration near the cathode, and produce rougher or less adherent deposits. The observed darker and rougher copper layers at 4.00 V and 5.00 V are consistent with the idea that deposition became less uniform at higher driving force. Prior electrodeposition studies have linked higher overpotentials and hydrogen evolution with more porous or irregular copper deposits [5].

A key limitation of the theoretical comparison is that current was not measured directly. The model used Ohm's law and assumed a constant effective resistance of 5.00 ohm, but an electrochemical cell does not necessarily behave as a simple fixed resistor throughout electrolysis. The more rigorous method would be to record current as a function of time and calculate charge from:

$$Q = \int I(t)dt$$

Without direct current data, the theoretical mass and calculated Faradaic efficiency should be treated as approximate indicators rather than definitive electrochemical efficiencies.

Despite these limitations, the investigation shows a practically important tradeoff. Increasing voltage can increase or maintain the amount of deposited copper within a fixed time, but higher voltage may reduce efficiency and deposit quality. This is relevant to electroplating and electrochemical process optimization, where maximizing production rate alone may not produce the most efficient or highest-quality coating [1,6].

Limitations and Future Work

Limitation	Effect on interpretation	Recommended improvement
Current was not measured directly.	Theoretical mass was estimated from voltage and an assumed resistance, so calculated Faradaic efficiency is approximate.	Use a functioning ammeter or data logger to record current continuously and calculate total charge by integration.
Mass changes were small relative to balance resolution.	The 1.00 V result and calculated efficiency are especially sensitive to rounding and drying error.	Use a balance with higher precision or increase electrolysis time so deposited masses are larger.
Cathode drying and rinsing could affect mass.	Residual water could overestimate mass, while loss of loosely attached copper could underestimate mass.	Use a standardized drying period, avoid wiping the deposit, and consider drying in a controlled environment.
Only three trials were conducted per voltage.	Random variation may not be fully represented.	Increase to five or more trials per voltage.
Temperature was controlled qualitatively rather than measured continuously.	Joule heating could change resistance, diffusion, and deposition behavior during trials.	Record solution temperature before and after each trial, or use a temperature-controlled water bath.
Surface morphology was assessed visually only.	Roughness and deposit quality were inferred but not quantitatively measured.	Use microscopy, image analysis, or surface roughness measurements to compare deposit morphology.
No 0 V control	A 0 V control would aid in determining whether copper mass gain occurred from non-electrolytic processes due to handling effects	Future work should include a 0.00 V control trial under the same conditions.

Conclusion

This study investigated how applied voltage affects copper electrodeposition and calculated Faradaic efficiency in a copper sulfate electroplating cell. The results showed that increasing voltage generally increased the mass of copper deposited over 300 s, with mean mass rising from 0.020 g at 1.00 V to approximately 0.050 g at 4.00 V. However, the mass deposited did not continue to increase substantially at 5.00 V, suggesting diminishing returns within the tested range. The calculated Faradaic efficiency decreased from approximately 101% at 1.00 V to 47% at 5.00 V under the idealized constant-resistance model. The apparent efficiency above 100% at 1.00 V reflects measurement resolution rather than a physically meaningful value. Overall, the results support the conclusion that voltage must be optimized rather than simply maximized: higher voltage can increase deposition rate but may reduce efficiency and coating quality because of non-ideal electrochemical behavior, side reactions, heating, and irregular deposition. Future work should directly measure current, monitor temperature, increase trial number, improve mass precision, and characterize deposit morphology to produce a more rigorous evaluation of copper electroplating efficiency.

Declarations

Funding: No external funding was received for this study.

Conflict of interest: The author declares no conflicts of interest.

Ethics approval: Not applicable; no human participants, animals, or living organisms were used.

Data availability: All data generated and analyzed during this study are included in this manuscript.

Author contribution: Arav Jain designed the investigation, conducted the experiment, analyzed the data, prepared the figures and tables, and wrote the manuscript.

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