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Investigation of micro channel fabrication by electroforming

Praveen Dasari

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A Thesis

Entitled

Investigation of Micro Channel Fabrication by Electroforming

by

Praveen Dasari

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Masters of Science degree in Mechanical Engineering

Dr. Ahalapitiya H. Jayatissa, Committee Chair

Dr. Mehdi Pourazady, Committee Member

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College of Graduate Studies

The University of Toledo

December 2010
An Abstract of

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Nanotechnology has the potential to create many new materials and devices with wide range of applications. Nanofabrication is the design and manufacture of devices with dimensions measured in nanometers. Development of an economic and reliable technique for the fabrication of reproducible micro channels has been an important challenge in this field. Feasibility of fabricating reproducible electrode gaps based on electroforming is investigated in this study.

The proposed technique is investigated by both theoretical modeling and experimental methods. Finite Element Analysis (FEA) technique is implemented to investigate the proposed hypothesis of fabrication of micro channels on thin films coated on insulator substrate. The gap formation for aluminum, gold, and tungsten oxide is attempted. The influence of various parameters on the heat transfer phenomenon during the electroforming is studied. Micro channel formation for gold is also investigated experimentally. Surface measurements were conducted to investigate the electroforming
process and the current-voltage characteristics are collected during the electroforming process. The experimental results obtained are compared with the Finite Element Analysis based modeling data.

The simulation and experimental results confirm the feasibility of the fabrication of micro gaps by the proposed electroforming technique. It is found that proposed method can be employed to produce micro channels using a wide range of materials such as metals, metal oxides and compound semiconductors.
This thesis is dedicated to my father Ajay Kumar Dasari, and mother Vedasree Dasari.
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List of Symbols

\( y_0 \) \ldots Length of height of the triangle area considered
\( y \) \ldots Distance measured in the direction shown
\( x_0 \) \ldots Length of height of the triangle area considered
\( x \) \ldots Distance measured in the direction shown
\( h \) \ldots Height of the tip
\( m \) \ldots Slope of the hypotenuse of the triangle considered
\( t_{th} \) \ldots Thickness of the coated material
\( R \) \ldots Resistance of the coated material
\( \rho \) \ldots Resistivity of the coated material
\( i \) \ldots Applied current
\( A \) \ldots Cross section area of strip
\( q \) \ldots Heat generated per unit volume
\( Q \) \ldots Heat generated
\( d_0 \) \ldots Density
\( c_p \) \ldots Specific heat
\( v \) \ldots Volume of the strip
\( \rho \) \ldots Resistivity at temperature \( u \),
\( \rho_{ref} \) \ldots Resistivity at temperature \( u_{ref} \) which is in general \( 0^\circ C \),
\( \text{cor} \) \ldots Temperature coefficient of resistance of the material
\( \rho_a \) .... Resistivity of aluminum,
\( \rho_g \) ...... Resistivity of gold \( u \),
\( B \) ...... Boltzmann’s constant
\( \Delta E \) ...... Activation energy,
\( u \) ...... Temperature
\( \alpha \) ...... Thermal diffusivity
\( t \) ...... Time
\( f \) ...... Source term for internal heat generation
\( a \) ...... Absorption coefficient
\( \alpha_c \) ...... Conservative flux convection coefficient
\( \gamma \) ...... Conservative flux source term
\( \beta \) ...... Convection coefficient
\( d_a \) ...... Damping/Mass coefficient
\( e_a \) ...... Mass coefficient
\( c \) ...... Diffusion coefficient
\( k_h \) ...... Heat conductivity
Chapter 1

Introduction

1.1 General Overview

The properties exhibited by materials when reduced to nanoscale were different and unique compared to what they show on a macroscale. Nanotechnology is the study of controlling of matter on an atomic and molecular scale. It deals with structures of size less than 100 nanometers. The interdisciplinary nature of nanotechnology with a reach encompassing chemistry, biology, physics, electronics and material science is more likely to yield innovations compared to traditional discipline based research [1].

Nanofabrication is the design and manufacture of devices with dimensions measured in nanometers. Complicated systems found in the nature could soon be built with the ever increasing role of nanofabrication in science and technology. The growing interest on molecular charge transport assessment in the field of nanofabrication was because of its potential applications in future nanoelectronic devices. This has spurred the development of nanoelectrodes which require gap sizes in the range of one or two nanometers.
1.2 Nanoelectrode, Importance of Micro and Nano Gaps

Nanoelectrode was defined as the electrode with a critical dimension that controls electrochemical response in the nanometer range. Decrease in size of electrodes to nanoscale has resulted in faster mass transport due to radial diffusion. Nanoelectrodes have stimulated the growth in the field of nanotechnology as they have wide applications in the study of transport phenomenon in nanoelectronic and molecular electronic devices. Fabrication of micro scale gap sizes was essential in applications of nanoelectrode. In realizing the use of metal-molecule-metal junctions as electronic components such as interconnects, diodes, and switches, lack of simple and reliable technique for fabricating micro nano gap has been the fundamental issue.

1.3 Methods for Fabrication of Micro and Nano Gaps

Many conventional lithographic techniques [2] have been developed to meet the demand for developing a economic, simple and reliable technique for fabricating micro and nano structures, including scanning probe microscopy techniques [3,4], mechanical break junctions [5], electro deposition [6], double angle evaporation [7, 8], electro migration [9, 10, 11, 12].

1.3.1 Conventional Lithographic Techniques

a) Electron beam lithography

Electron beam lithography was used for direct primary patterning of computer designed pattern. It was not suitable for mass production because of its limited writing speed. The resolution of Electron beam lithography was defined by the electron beam spot size and the forward scattering range of the electrons. This method has been used for hole-drilling, contamination induced growth and also for
surface modification of inorganic materials. This method possesses parallel writing feasibility enabling the fabrication of parallel arrays.

b) Focused ion beam lithography

Focused ion beam (FIB) technology [13, 14, and 15] has also been employed in nanoelectrode manufacturing. Precise control and direct fabrication of nanostructures were possible because of small spot size and low lateral exposure of FIB. The speed of nanocutting and reproducibility were the main advantages of FIB milling although either ion induced deposition or milling have to be used in this method. The smaller magnitude of ion beam current density compared to electron beams limits the speed in spite of high ion sensitivity of resists.

c) Optical projection lithography

In this method a photo resist was exposed to deep ultraviolet light through a mask containing alternate opaque and clear features. This method was suitable for mass production. Application of this method to issues like mask fabrication, sensitive high resolution resists was being investigated.

d) Extreme UV lithography

Extreme UV lithography refers to the exposure technique developed with a reflective reduction system and the radiation obtained from laser-induced plasmas. The radiation was projected on to a reflective mask and then focused on to the wafer. Its main advantage was its potentiality for several generation manufacturing. Fabrication of high precision optical elements, mask optimization, alignment, and feedback control were some of the challenges of this method to be overcome.
e) X-ray lithography

Fresnel diffraction and the photoelectron diffusion were the main factors influencing the resolution of X-ray lithography. Mechanical stability and alignment have been the main challenges for X-ray lithography to be used industrially.

f) Electron and ion projection lithography

In electron and ion projection lithography scattered electron interactions resulting in wafer heating and expansion limit the production rate. The challenges of this method like deposition of energy, uniformity in source were needed to be further investigated for industrial application of this method.

1.3.2 Scanning Probe Microscopy Techniques

A molecular junction composed of a monolayer on metal surface was probed by a tip which interact with one or two molecules and results in the gap formation. Scanning Probe Microscopy was carried out either by Scanning Tunneling Microscope or by a Conducting Probe Atomic force Microscope. This technique was based on single molecule junctions by controlling the conductance in the junctions. The electron transfer behavior of these junctions was related to that of donor-acceptor molecules.

1.3.3 Mechanical Break Junctions

It has been recently proved that self breaking technique was efficient in avoiding nanoparticle formations. A nanosized metal junction was thinned by electro migration procedures by applying bias ramps repetitively to gradually shrink the nanoconstruction in this method. Use of molecular break junctions has been most convincing for transport characteristics through single or small number of
molecules as the gap length can be controlled in this method. So the area of producing nanogap devices with gap fabricated commensurate with the molecules of interest was under focus.

1.3.4 Electro Deposition
In this technique gap size of predefined electrode pairs was narrowed by electrochemical narrowing. Fabrication of atomic scale separation gaps characterized by quantum conductance effect was possible by electro deposition. A versatile electrochemical method to fabricate nanogaps with adjustable gap size is yet to be developed.

1.3.5 Double angle Evaporation
In this method an undercut was made with the help of electron beam lithography after depositing a thin metal layer on a substrate. Then another metal layer was deposited at an angle a gap was formed under the suspended resist bridge. The first metal was evaporated perpendicular to substrate for deposition where as the second metal was evaporated at an angle to the substrate. In this method the accuracy of the gap depends on the granularity of the metals but not on the lithography process. This method allows integrating nanogaps and the only limiting factor for this was the size of undercut.

1.3.6 Electro Migration
Electro migration was defined as the process of migration of atoms in a metal from one region to another through accelerated electron bombardment. This was the crucial phenomenon in design and main limiting factor of lifetime for integrated circuits. Electro migration was affected by several variables, namely the size and
properties of interconnects, current density, and the stressing conditions (temperature and material diffusion rates). Fabrication of nanosized gaps was possible if the process was dominated by electro migration and joule heating and also the resulting melting and surface tension effects were limited. For nanogap formation high current density and high atomic mobility for substantial occurrence of mass flow were essential and prevention of excess of heating has been a challenging problem. Studies were carried out to control electro migration in nanowires by incorporating a feedback mechanism so that the process gets slowed down once the wire starts thinning down. The series resistance was also controlled to limit the temperature. The interplay between joule heating and electro migration has to be further investigated for reliable nanogap formation.

1.4 Applications of Nanoelectrode

- Nanoelectrodes because of their enhanced mass transport rates can be used to measure the kinetics of faster electrode reactions [16]. The study of faster electrochemical and chemical reactions was enhanced stimulating the development in the field of physical electrochemistry.

- Nanoelectrodes have potential applications in scanning electrochemical microscopy (SECM) for mapping electrochemical activity of greater resolution than possible by micrometer sized electrodes. Nanoelectrodes have application in fabricating phase change random access memory (PCRAM) to improve performance, reducing cost increasing compatibility and throughput of the device [17].
• Remarkable applications in nanotechnology have been materialized because of accelerated synchronous growth in instrumentation, molecular biology and material science. Nanoelectrodes have been applied for ultra sensitive detection methodologies and also great potential was shown for the development of efficient, sensitive and intelligent devices [18].

• Accurate and reliable glucose monitoring has been possible with the fabrication of glucose biosensor which was a crucial development in the treatment of diabetes. Nanoelectrode ensembles have been applied in the fabrication of glucose biosensors [19].

• Nanosized gold particles immobilized on gold nanoelectrode has potential application for fabrication of voltammetric Dopamine sensor [20]. Accurate detection of Dopamine, one of the most important neurotransmitters would be a significant achievement in the field of neurology.

• Development of a simple reliable technique for Deoxyribonucleic acid (DNA) detection was essential for the enhancements in the modern life science of diagnosis and drug discovery. A highly sensitive sensor was fabricated based on a nanogapped gold particle film utilizing alkyldithiol as binder molecule for detecting DNA [21].

1.5 Need for New Fabrication Method

The greatest challenge being faced for realization of discussed benefits was the lack of a simple and reliable method for the fabrication of electrode gaps in the range of micrometers. A fabrication technique which opens possibilities for the production of reproducible electrode gaps was presented in this study.
1.6 Proposed Fabrication Method

Figure 1-1: Mechanism of Proposed Fabrication Method.

2. Insulator Substrate.
3. Coated Thin Film.
4. Location of Gap formation.
A thin film of given material was coated on an insulator substrate in the shape shown in Figure 1-1.

Electric current was applied with power supply.

Maximum resistance to the applied current in the thin coated film was offered at the location shown with minimum amount of material.

As the resistance was high, heat generated was maximum at this point and the material gets melted when the temperature reaches the melting point of the film material.

The gap was formed as a result and the current suddenly becomes zero as there was no path for its flow.

The size of the gap formed was to be optimized by controlling the parameters like shape, current and material of the coated film.

1.7 Thesis Outline

- Chapter 1

The objective of this study is to investigate fabrication of electrode gaps by electroforming. The central hypothesis is controllable micro and nano structures could be manufactured by applying electric current on materials coated in desired shape on insulator substrate.

- Chapter 2

Equations are derived for the heat generated due to applied current taking the shape, material and the applied current into account. Equations for variation of resistivity with temperature for metals and semi conductors are derived and the entire phenomenon is modeled based on heat transfer equations.
• Chapter 3

Finite Element model is developed for the heat transfer equation by using COMSOL finite element package. The various dimension sets considered and various cases of simulation chosen are reported.

• Chapter 4

The steady state and transient state responses for the model are generated. The influence of various parameters on the gap formation was investigated and the obtained results were reported and analyzed.

• Chapter 5

The experimental procedure of application of current on thin film is explained. The microscopic images of experimentally formed gaps are presented. Representative breaking curves are generated and simulation results are verified experimentally for gold.
Chapter 2

Numerical Model

2.1 Numerical Model Overview

- The heating mechanism of the proposed fabrication method was modeled as a heat transfer model.
- The heat generated due to the resistance offered to the applied current was modeled as internal heat generated in the heat transfer problem.

Figure 2-1: Shape of the Coated Thin Film.
• Instead of developing the numerical model for the entire shape only the shaded area was considered taking advantage of symmetry.
• Equation for the heat generated because of resistance offered to the applied current was derived taking shape, material, and applied current in to consideration.
• Equations for variation of resistivity with temperature for metals and semiconductors were derived.
• Thermal diffusivities for the considered materials were derived.
• The heat transfer equation was modeled and all the terms were dimensionally verified

2.2 Derivation for Heat Generated per Unit Volume

Variables used for the derivation of heat generated per unit volume due to application of current on the considered shaded area.

\[ y_0 \]  Length of height of the triangle area considered  
\[ y \]  Distance measured in the direction shown  
\[ x_0 \]  Length of height of the triangle area considered  
\[ x \]  Distance measured in the direction shown  
\[ h \]  Height of the tip  
\[ m \]  Slope of the hypotenuse of the triangle considered
A strip of width $dx$ considered with height $y$ as shown in the Figure 2-2;

$$y = y_0 - (m \times x). \quad (2.1)$$

Heat generated per unit volume;

$$Q = R \times i^2. \quad (2.2)$$
Heat generated per unit volume; 
\[ q = \frac{R \times i^2}{v}. \] (2.3)

Resistance offered by the considered strip; 
\[ R = \left[ \frac{\rho \times dx}{A} \right]. \] (2.4)

Volume of the strip; 
\[ v = t_{th} \times (y_0 - (m \times x)) \times dx. \] (2.5)

Cross section area of the strip 
\[ A = t_{th} \times (y_0 - (m \times x)). \] (2.6)

Heat generated per unit volume obtained by substituting Equations 2.3, 2.4, and 2.5 in Equation 2.2

\[ q = \frac{\rho \times dx \times i^2}{t_{th} \times (y_0 - (m \times x)) \times t_{th} \times (y_0 - (m \times x)) \times dx} \]

\[ q = \left[ \frac{\rho \times i^2}{t_{th}^2 \times (y_0 - (m \times x))^2} \right]. \] (2.7)

2.3 Thermal Properties

- Heat conductivity \( k_h \) was the ability of a material to conduct heat.
- Density \( d_0 \) of material was defined as the mass per unit volume.
- Specific heat \( c_p \) of material was the ratio of the amount of heat required to raise the temperature of a unit mass of a substance by one unit of temperature to the amount of heat required to raise the temperature of a similar mass of a reference material, usually water, by the same amount.
- Melting point of the material was the minimum temperature at which the material starts melting.
Thermal diffusivity was defined as the heat conductivity divided by volumetric heat capacity. It was calculated from Equation 2.8 [22]

\[
\text{Thermal diffusivity} = \left[ \frac{k_h}{d_0 \times c_p} \right]. \tag{2.8}
\]

The Thermal diffusivity value was calculated for gold and tungsten oxide from the Equation 2.8. The value for used for aluminum was available in the literature [23].

Table 2.1: Thermal properties of gold and aluminum

<table>
<thead>
<tr>
<th>Property</th>
<th>gold</th>
<th>aluminum</th>
<th>tungsten oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conductivity $k_h$</td>
<td>$318 W/m^0C$</td>
<td>$237 W/m^0C$</td>
<td>$1.63 W/m^0C$</td>
</tr>
<tr>
<td>Density $d_0$</td>
<td>19,320kg/m$^3$</td>
<td>2,700kg/m$^3$</td>
<td>7160kg/m$^3$</td>
</tr>
<tr>
<td>Specific heat $c_p$</td>
<td>$126 J/kg^0C$</td>
<td>$900 J/kg^0C$</td>
<td>$669.44 J/kg^0C$</td>
</tr>
<tr>
<td>Melting point</td>
<td>$1064.18^0C$</td>
<td>$660.32^0C$</td>
<td>$1473^0C$</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>$1.306 \times 10^{-4} m^2/s$</td>
<td>$8.418 \times 10^{-5} m^2/s$</td>
<td>$3.4 \times 10^{-7} m^2/s$</td>
</tr>
</tbody>
</table>

The values for thermal properties of gold and aluminum listed in Table 2.1. These were the commonly used property values verified from Wikipedia. The values for thermal properties of tungsten oxide were verified in number of sources [24, 25, and 26]. Although these thermal properties show some variation with temperature they were assumed to be constant in this analysis.
2.4 Electrical Resistivity

- Electrical resistivity was the measure of strength of opposition offered to the flow of current. It was also defined as the inverse of conductivity. Its units are $\Omega \cdot m$.

- Electrical resistivity was not a constant and it varies with temperature because of electron photon interactions in the material.

- In general electrical resistivity of metals increases with temperature, while the resistivity of semiconductors decreases with increasing temperature.

- The variation of resistivity with temperature for metals was linear and exponential for semiconductors.

2.4.1 Variation of Resistivity of Metals with Temperature.

The variation of resistivity of metals with temperature was modeled with the Equation 2.8 [27, 28].

$$\rho = \rho_{ref} \left[1 + \text{cor}(u - u_{ref})\right]$$  \hspace{1cm} (2.8)

$\rho$  Resistivity at temperature $u$,

$\rho_{ref}$  Resistivity at temperature $u_{ref}$ which is in general $0^\circ C$,

$\text{cor}$  Temperature coefficient of resistance of the material

2.4.1.1 Equation for variation of resistivity of aluminum

The variables in Equation 2.8 were substituted with the values for aluminum [28, 30] to get the Equation 2.9

$$\rho_m = (1 + (0.004308 \times (u - 20))) \times 2.655 \times 10^{-8} \Omega \cdot m$$  \hspace{1cm} (2.9)
2.4.1.2 Equation for variation of resistivity of gold

The resistivity variation equation for gold was developed from the resistivity values available at different temperatures [29]. A graph was drawn for resistivity values with increasing temperature and a trend line framed for the graph would be used as the equation for variation of resistivity of gold. This equation obtained was slightly different from Equation 2.8 as there was slight variation between the trend line and actual plot.

![Graph](image)

Figure 2-3: Variation of resistivity of gold with temperature.

\[
\rho_g = (0.0083 \times (u + 273)) \times 10^{-8} \Omega \cdot m
\]  \hspace{1cm} (2.10)
2.4.2 Variation of Resistivity of Semiconductors with Temperature.

The variation of resistivity of semiconductor with temperature was modeled with the Equation 2.11 [32, 33].

\[
\rho = \rho_{ref} \times \exp \left[ \frac{\Delta E}{B \times u} \right]
\]  
(2.11)

\(\rho\)  Resistivity at temperature \(u\),

\(\rho_{ref}\)  Resistivity at temperature \(u_{ref}\),

\(\Delta E\)  Activation energy,

Boltzmann’s constant \(B = 8.617343 \times 10^{-5}\).

The resistivity equations for tungsten oxide were derived for two values of activation energy i.e. \(\Delta E = 0.3eV\) and \(\Delta E = 0.4eV\)

For Activation energy \(\Delta E = 0.3eV\), the value of \(\rho_{ref}\) was calculated by considering the

\[
2 \times 10^{-4} = \rho_{ref} \exp \left[ \frac{0.3}{8.617343 \times 10^{-5} \times (273 + 980)} \right] \Omega \cdot m
\]

\[
\rho_{ref} = 1.242 \times 10^{-5} \Omega \cdot m
\]  
(2.12)

The variables in Equation 2.11 were substituted with the values for tungsten oxide [34, 35] and Equation 2.12 to get the variation of resistivity equation.

Resistivity of tungsten oxide for \(\Delta E = 0.3eV\);

\[
\rho = 1.242 \times 10^{-5} \exp \left[ \frac{3481.35}{273 + u} \right] \Omega \cdot m
\]  
(2.13)
For Activation energy $\Delta E = 0.34V$, the value of $\rho_{ref}$ was calculated by considering the

$\rho = 2 \times 10^{-4}$ at $u = 980^0C$ [25] and substituting in Equation 2.11.

$$2 \times 10^{-4} = \rho_{ref} \exp \left[ \frac{0.4}{8.617343 \times 10^{-5} \times (273 + 980)} \right] \Omega \cdot m$$

$$\rho_{ref} = 4.92 \times 10^{-6} \Omega \cdot m \quad (2.14)$$

The variables in Equation 2.11 were substituted with the values for tungsten oxide and Equation 2.14 to get the variation of resistivity equation.

Resistivity of tungsten oxide for $\Delta E = 0.4eV$;

$$\rho = 4.92 \times 10^{-6} \exp \left[ \frac{4641.80}{273 + u} \right] \Omega \cdot m \quad (2.15)$$

### 2.5 Modeled Heat Transfer Equation.

The heating mechanism of the proposed fabrication method was modeled as a two dimensional heat transfer equation with internal heat generation [36].

$$\frac{\partial u}{\partial t} = \alpha \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right] + f \quad (2.16)$$

$u$ Temperature in $^0C$

$\alpha$ Thermal diffusivity in $\frac{m^2}{s}$

$t$ Time

$f$ Source term for internal heat generation
\[ f = \left[ \frac{q}{d_0 \cdot c_p} \right] \]  

(2.17)

Substituting value of \( q \) from Equation 2.7 in Equation 2.17 to get the source term

\[ f = \left[ \frac{\rho \times i^2}{d_0 \times c_p \times t_{th}^2 \times (y_0 - (m \times x))^2} \right] \]  

(2.18)

The modeled heat transfer equation was

\[ \frac{\partial u}{\partial t} = \alpha \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right] + \left[ \frac{\rho \times i^2}{d_0 \times c_p \times t_{th}^2 \times (y_0 - (m \times x))^2} \right] \]  

(2.19)

The application of current on the metal film was carried out in vacuum so heat transfer in the lateral direction was ignored. Along the base and tip of the considered triangular shape insulated boundary condition was assumed as there would not be any heat flow from these sides. The boundary condition on the height and the hypotenuse were assumed to be at room temperature.

**2.6 Dimensional Verification of the Modeled Heat Transfer Equation.**

From [37]

\[ \Omega \times i^2 = \frac{J}{s} \]  

(2.20)

Third term in Equation 2.19;

\[ \frac{\rho \times i^2}{d_0 \times c_p \times t_{th}^2 \times (y_0 - (m \times x))^2} = \frac{\Omega \cdot L \times i^2}{\frac{kg \times J}{m^3} \times \frac{C}{kg \cdot 0 \times L^2 \times L^2}} \]

Using Equation 2.20

\[ \Rightarrow \frac{^0 \text{C} \times \Omega \times i^2}{J} = \frac{^0 \text{C} \times J}{s} = \frac{^0 \text{C}}{s} \]  

(2.21)
As all the terms in the Equation 2.19 were of same units \(\frac{\circ C}{s}\), the modeled equation was dimensionally correct.

2.7 Chapter Conclusions

The amount of heat generated per unit volume because of application of current was derived. The equation for variation of resistivity with temperature for metals gold, aluminum and semiconductors tungsten oxide were derived. Thermal properties of gold, aluminum tungsten oxide used in the simulation were presented. The proposed fabrication phenomenon was modeled as a two dimensional heat transfer equation. The modeled heat transfer equation was dimensionally verified.
Chapter 3

Finite Element Modeling

3.1 Finite Element Model Overview

In this analysis feasibility of producing micro and nano gaps by proposed electroforming method was investigated. The modeling discussed in this chapter includes a two dimensional finite element network model developed for the derived heat transfer equation. The phenomenon is simulated with the help of COMSOL finite element package, commercial software for equation based Multiphysics modeling.

The thermal properties discussed and the resistivity equations derived in Chapter 2 were used in the finite element analysis. Simulations were run for various dimensions of the considered shape for gold, aluminum and tungsten oxide.

- The model was analyzed for the following cases.
  a) Steady state Response.
  b) Transient state Response.
  c) Modeling current as the linear equation of time.
3.2 Finite Element Analysis

Finite element analysis was a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. All types of scientific and engineering problems based on differential and integral equations could be solved using the finite element method with reasonable assumptions. Finite element analysis gives approximate solutions which would be very near to the exact solutions.

3.3 Equation Considered in COMSOL Partial Differential Equation Modes

\[ e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \cdot (\gamma \nabla u - au + \beta) + au + \beta \nabla u = f. \]  

(3.1)

Table 3.1: Values for the parameters in Equation 3.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Absorption coefficient</td>
<td>0</td>
</tr>
<tr>
<td>(\alpha_c)</td>
<td>Conservative flux convection coefficient</td>
<td>0</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Convection coefficient</td>
<td>0</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Conservative flux source term</td>
<td>0</td>
</tr>
<tr>
<td>(d_a)</td>
<td>Damping/Mass coefficient</td>
<td>1</td>
</tr>
<tr>
<td>(e_a)</td>
<td>Mass coefficient</td>
<td>0</td>
</tr>
<tr>
<td>(c)</td>
<td>Diffusion coefficient</td>
<td>Thermal diffusivity of material considered material considered</td>
</tr>
<tr>
<td>(f)</td>
<td>Source term</td>
<td>Used from Equation 2.18</td>
</tr>
</tbody>
</table>
The boundary condition used was Dirichlet \( p \cdot u = r. \) \( \tag{3.2} \)

insulated for the base \( x_0 \) and tip \( h \)

\( p = 0 \) \( \tag{3.3} \)

The boundary conditions were assumed to be at \( 25^\circ C \) for the hypotenuse and the height \( y_0 \)

\( p = 1 \quad r = 25. \) \( \tag{3.4} \)

Initial condition was

\( u(t_0) = 25. \) \( \tag{3.5} \)

3.4 Different Dimensions Employed for Simulation

The dimensions of the considered triangular shape were varied in the simulation to study their effect on the amount of current needed to reach the melting point temperature.

![Dimensional view of considered shape.](image)

Figure 3-1: Dimensional view of considered shape.
Various dimension sets of the considered shape shown in Figure 3-1 employed for the simulation were presented in the Table 3.2. The simulations were carried out for all these dimension sets for materials gold, aluminum and tungsten oxide.

Table 3.2: Various dimension sets used for simulation

<table>
<thead>
<tr>
<th>set</th>
<th>( y_0 ) (mm)</th>
<th>( x_0 ) (mm)</th>
<th>( h ) (mm)</th>
<th>( m ) (slope of hypotenuse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.05</td>
<td>4</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>B</td>
<td>1.10</td>
<td>4</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>C</td>
<td>1.15</td>
<td>4</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>D</td>
<td>2.05</td>
<td>4</td>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>2.10</td>
<td>4</td>
<td>0.10</td>
<td>0.5</td>
</tr>
<tr>
<td>F</td>
<td>2.15</td>
<td>4</td>
<td>0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>G</td>
<td>3.05</td>
<td>4</td>
<td>0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>H</td>
<td>3.10</td>
<td>4</td>
<td>0.10</td>
<td>0.75</td>
</tr>
<tr>
<td>I</td>
<td>3.15</td>
<td>4</td>
<td>0.15</td>
<td>0.75</td>
</tr>
<tr>
<td>J</td>
<td>4.05</td>
<td>4</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td>4.10</td>
<td>4</td>
<td>0.10</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>4.15</td>
<td>4</td>
<td>0.15</td>
<td>1</td>
</tr>
</tbody>
</table>

3.5 Mesh Generation

- The shape considered was drawn with the help of lines points and planes. Complex shapes if required could be imported directly from cad software with the feature present in COMSOL.
The boundary conditions, initial conditions and the input for different variables in the equation were specified as described in the section 3.3.

The material properties were specified as described in Chapter 2 in the sub domain settings depending the material selected.

The domain was divided as number of sub domains in this case two dimensional triangular elements as shown in Figure 3-3 to obtain the solution.

The accuracy of the solution depends on the number of elements in the mesh. Higher mesh density i.e. more number of elements increases accuracy at the cost of computational time.

The mesh is not uniform throughout the domain. It is finer at sharp edges or corners to increase the accuracy of solution obtained. In the Figure 3-3 it could be observed that the mesh is finer towards the tip.
Mesh density plays a critical role in the accuracy of results obtained for complex geometries. As the shape considered in this analysis was simple finer mesh was not essential for accurate results.

Defining mesh and selection of elements were crucial in the overall accuracy of the obtained solution.

### 3.6 Different Cases Analyzed

1. Steady state response.
   
   In steady state condition there was no variation in temperature with time as the result was obtained at the end of process. In this case the current was supposed to be applied for one second and the temperature profile of the considered shape was
obtained at the end of second. The value of current for which the maximum
temperature reaches the melting point for different sets of dimensions considered,
different thicknesses were reported for gold, aluminum, and tungsten oxide.

2. Transient Response.

In transient condition there was variation in temperature with time as the result
was obtained at the intermediate step. In this case the current was supposed to be
applied for one second and the temperature profile of the considered shape was
obtained at an intermediate time step. The applied current value was more than
that of the steady state value so that melting point temperature was reached before
the steady state. Finer gaps were reported to be formed in case of transient
response. The temperature profile at any intermediate time step could be obtained.

3. Applied current as the linear equation of time.

The current was applied as a linear equation of time with a feature present in the
solution parameters. The response was steadied when same amount current was
applied varying the time of application. The obtained temperature profile were
analyzed and reported for gold, aluminum and tungsten oxide. It was observed
that the location of melting point temperature in this case was far away from the
tip suggesting the increased gap sizes. Transient state response in this case was
not investigated as the formation of nano sized gaps was not possible in this case.
So for the proposed fabrication method the application of current should be
instantaneous.
3.7 Chapter Conclusions

Finite element analysis, mesh generation process were explained. The equation considered in COMSOL Partial Differential Equation Modes was presented. Different dimension sets of the considered shape employed for the simulation were presented. Various simulation cases chosen for analysis were listed.
Chapter 4

Results and Discussion

4.1 Results Overview

The heat transfer phenomenon and practical applicability of the proposed fabrication method was investigated for metals gold, aluminum and semiconductor tungsten oxide. The influence of various parameters on the gap formation was investigated for different dimensions sets, thicknesses and materials. The amounts of current needed for reaching the melting point temperature were estimated and comparative study for gold, aluminum and tungsten oxide was carried out. The influence of activation energy in case of tungsten oxide was also studied. The variation of resistivity over the surface during the application of current was also investigated.

4.2 Effect of Dimensions on Amount of Current Applied for Gold

Figure 4-1 was the plot for amount of currents required for melting point temperatures to be reached for different thicknesses and heights $y_0$ of the considered triangular area. It was observed from Figure 4-1 that for gold amount of current required for reaching
melting point temperatures i.e. formation of gap increases with thickness of the film and also with the size of the film i.e. the height of the triangular shape.

![Graph showing variation of current applied with height of triangular shape](image)

Figure 4-1: Variation of current applied with height of triangular shape considered to reach melting point temperature for gold.

### 4.3 Variation of Resistivity along the Considered Triangular Shape during the Application of Current for Gold.

Figure 4-2 was the plot for variation of electrical resistivity along the base $x_0$ of the considered triangular shape for gold during the application of current for set D and 100 nanometers thickness. It was observed that the resistivity at the tip increases during the application of current resulting in maximum heat generation at that location. The gap would be formed at the tip when melting point temperature was reached.
Figure 4-2: Variation of resistivity along the base of triangular shape for gold.

4.4 Steady State Response for Gold

The 2D surface plot of steady state response for gold when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-3 for set D and 100 nanometers thickness.
Figure 4-3: 2D surface plot of gold when melting point temperature was reached at steady state for set D and 100 nanometers thickness.

Figure 4-4 was the same plot as Figure 4-3 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D plot. The height and the color represent the temperature scale.
Figure 4-4: 3D surface plot of gold when melting point temperature was reached at steady state for set D and 100 nanometers thickness.

The applied current in this case was 268.7 mA. If melting point temperature was reached at steady state condition, it was observed from Figure 4-3, that the location of melting point temperature was at the tip. This was due to the maximum resistance to the applied current at that location. It was also observed from Figure 4-4, that heat was distributed along the entire area of film which was not desired.
4.5 Response when Boundary Condition of Hypotenuse was varied for Gold

The 2D surface plot of steady state response for gold when the melting point temperature was reached at the location of maximum temperature after changing the boundary condition of the hypotenuse as thermally insulated was shown in Figure 4-5 for set D and 100 nanometers thickness.

Figure 4-5: 2D surface plot of gold when boundary condition of hypotenuse was thermally insulated for set D and 100 nanometers thickness.
It was observed from Figure 4.5 that the heat distribution was better throughout the surface and the temperature along the hypotenuse varies during the heat application process. The melting point temperature was observed to be at the tip.

Figure 4-6: 2D surface plot of gold when temperature of the hypotenuse was increased to 600 degrees centigrade for set D and 100 nanometers thickness.

It was observed from Figure 4.6 that the heat distribution in this case was intermediate to the two previously considered hypotenuse boundary condition cases. The melting point temperature was observed to be at the tip. The assumption that temperature along the
hypotenuse was higher throughout the heating does not hold good the temperature profile obtained in this case was very near to the practical situation.

4.6 Transient Response for Gold

Figure 4-7: 2D surface plot of gold when melting point temperature was reached in transient state for set D and 100 nanometers thickness.

The 2D surface plot of transient state response for gold when the melting point temperature was reached at the location of maximum temperature was shown in the Figure 4-7 for set D and 100 nanometers thickness.
Figure 4-8: 3D surface plot of gold when melting point temperature was reached in transient state for set D and 100 nanometers thickness.

Figure 4-8 was the same plot as Figure 4-7 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D plot. The applied current was changed to 275 mA to get transient response by leaving all other parameters same as that of steady state. It was observed that the melting point temperature was reached in transient state from Figure 4-8. From Figure 4-7 it was observed that the heat was concentrated at the tip. The material gets melted after reaching
the melting point temperature resulting in gap formation and prevents further current flow.

4.7 Effect of Dimensions on Amount of Current Applied for Aluminum

Figure 4-9: Variation of electrical resistivity along the base $x_0$ of the considered triangular shape for aluminum during the application of current for set D and 100 nanometers thickness. It was observed that the resistivity at the tip increases during
the application of current resulting in maximum heat generation at that location. The gap would be formed at the tip when melting point temperature was reached.

4.8 Variation of Resistivity along the Considered Triangular Shape during the Application of Current for Aluminum.

![Graph showing variation of resistivity along the base of triangular shape for aluminum.](image)

Figure 4-10: Variation of resistivity along the base of triangular shape for aluminum.

Figure 4-10 was the plot for variation of electrical resistivity along the base $x_0$ of the considered triangular shape for aluminum during the application of current for set D and 100 nanometers thickness. It was observed that the resistivity at the tip increases during
the application of current resulting in maximum heat generation at that location. The gap would be formed at the tip when melting point temperature was reached.

4.9 Steady State Response for Aluminum

Figure 4-11: 2D surface plot of aluminum when melting point temperature was reached at steady state for set D and 100 nanometers thickness.

The 2D surface plot of steady state response for aluminum when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-11 for set D and 100 nanometers thickness.
Figure 4-12: 3D surface plot of aluminum when melting point temperature was reached at steady state for set D and 100 nanometers thickness.

Figure 4-12 was the same plot as Figure 4-11 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D plot. The applied current in this case was 176.5 mA. If melting point temperature was reached at steady state condition, it was observed from Figure 4-11, that the location of melting point temperature was at the tip. It was also observed from Figure 4-12, that heat was distributed along the entire area of film which was not desired.
4.10 Response when Boundary Condition of Hypotenuse was varied for Aluminum

Figure 4-13: 2D surface plot of aluminum when boundary condition of hypotenuse was thermally insulated state for set D and 100 nanometers thickness.

The 2D surface plot of steady state response for aluminum when the melting point temperature was reached at the location of maximum temperature after changing the boundary condition of the hypotenuse as thermally insulated was shown in Figure 4-13 for set D and 100 nanometers thickness.
It was observed from Figure 4.13 that the heat distribution was better throughout the surface and the temperature along the hypotenuse varies during the heat application process. The melting point temperature was observed to be at the tip.

Figure 4-14: 2D surface plot of aluminum when temperature of the hypotenuse was increased to 600 degrees centigrade for set D and 100 nanometers thickness.

It was observed from Figure 4.14 that the heat distribution in this case was intermediate to the two previously considered hypotenuse boundary condition cases. The melting point temperature was observed to be at the tip. The assumption that temperature along the
hypotenuse was higher throughout the heating does not hold well the temperature profile obtained in this case was very near to the practical situation.

### 4.11 Transient Response for Aluminum

![Figure 4-15: 2D surface plot of aluminum when melting point temperature was reached in transient state for set D and 100 nanometers thickness.](image)

Figure 4-15: 2D surface plot of aluminum when melting point temperature was reached in transient state for set D and 100 nanometers thickness.

The 2D surface plot of transient state response for aluminum when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-15 for set D and 100 nanometers thickness.
Figure 4-16: 3D surface plot of aluminum when melting point temperature was reached in transient state for set D and 100 nanometers thickness.

Figure 4-16 was the same plot as Figure 4-15 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D plot. The applied current was changed to 183.4 mA to get transient response by leaving all other parameters same as that of steady state. It was observed that the melting point temperature was reached in transient state from Figure 4-15, and also the location of melting point temperature was close at the tip. From Figure 4-16 it was observed that the
heat was concentrated at the tip. The material gets melted after reaching the melting point temperature resulting in gap formation and prevents further current flow.

4.12 Effect of Dimensions on Amount of Current Applied for Tungsten Oxide with 0.3 eV Activation Energy

Figure 4-17: Variation of current applied with height of triangular shape considered to reach melting point temperature for tungsten oxide with activation energy 0.3eV.

Figure 4-17 was the plot for amount of currents required for melting point temperatures to be reached for different thicknesses and heights $y_0$ of the considered triangular area. It was observed from Figure 4-17 that for tungsten oxide with activation energy 0.3eV,
amount of current required for reaching melting point temperatures i.e. formation of gap increases with thickness of the film and also with the size of the film i.e. the height of the triangular shape.

4.13 Effect of Dimensions on Amount of Current Applied for Tungsten Oxide with 0.4 eV Activation Energy

![Figure 4-18: Variation of current applied with height of triangular shape considered to reach melting point temperature for tungsten oxide with activation energy 0.3eV.](image)

Figure 4-18: Variation of current applied with height of triangular shape considered to reach melting point temperature for tungsten oxide with activation energy 0.3eV.

Figure 4-18 was the plot for amount of currents required for melting point temperatures to be reached for different thicknesses and the height $y_0$ the considered triangular area. It
was observed from Figure 4-19 that for tungsten oxide with activation energy 0.4 eV, amount of current required for reaching melting point temperatures i.e. formation of gap increases with thickness of the film and also with the size of the film i.e. the height of the triangular shape.

4.14 Steady State Response for Tungsten Oxide with 0.3 eV Activation energy

Figure 4-19: 2D surface plot of tungsten oxide with activation energy 0.3 eV when melting point temperature was reached at steady state for set D and 250 nanometers thickness.
The 2D surface plot of steady state response for surface plot of tungsten oxide with 0.3 eV activation energy when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-19 for set D and 250 nanometers thickness.

Figure 4-20: 3D surface plot of tungsten oxide with activation energy 0.3 eV when melting point temperature was reached at steady state for set D and 250 nanometers thickness.

Figure 4-20 was the same plot as Figure 4-19 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D
plot. The applied current in this case was 1.22 mA. If melting point temperature was reached at steady state condition the location of melting point temperature was at the tip. It was also observed from Figure 4-20 that heat was distributed along the entire area of film which was to be avoided for reliable gap formation.

4.15 Transient Response for Tungsten Oxide with 0.3 eV Activation energy

![Figure 4-21: 2D surface plot of tungsten oxide with activation energy 0.3 eV when melting point temperature was reached in transient state for set D and 250 nanometers thickness.](image)
The 2D surface plot of steady state response for surface plot of tungsten oxide with 0.3 eV activation energy when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-21 for set D and 250 nanometers thickness.

Figure 4-22: 3D surface plot of tungsten Oxide with 0.3 eV activation energy when melting point temperature was reached in transient state for set D and 250 nanometers thickness.

Figure 4-22 was the same plot as Figure 4-21 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D.
plot. The applied current was changed to 1.4 mA to get transient response by leaving all other parameters same as that of steady state. It was observed that the melting point temperature was reached in transient state from heat was concentrated at the tip. The material gets melted after reaching the melting point temperature and prevents further current flow.

**4.16 Steady State Response for Tungsten Oxide with 0.4 eV Activation energy**

![Figure 4-23: 2D surface plot of tungsten oxide with 0.4 eV activation energy when melting point temperature was reached at steady state for set D and 250 nanometers thickness.](image)

Figure 4-23: 2D surface plot of tungsten oxide with 0.4 eV activation energy when melting point temperature was reached at steady state for set D and 250 nanometers thickness.
The 2D surface plot of steady state response for surface plot of tungsten oxide with 0.4 eV activation energy when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-23 for set D and 250 nanometers thickness.

Figure 4-24: 3D surface plot of tungsten Oxide with 0.3 eV activation energy when melting point temperature was reached at steady state for set D and 250 nanometers thickness.

Figure 4-24 was the same plot as Figure 4-23 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D plot. The applied current in this case was 1.15 mA. If melting point temperature was
reached at steady state condition that the location of melting point temperature was at the tip. It was also observed from Figure 4-24 that heat was distributed along the entire area of film which was to be avoided for reliable gap formation.

4.17 Transient Response for Tungsten Oxide with 0.4 eV Activation energy

Figure 4-25: 2D surface plot of tungsten oxide with activation energy of 0.4 eV when melting point temperature was reached in transient state for set D and 250 nanometers thickness.

Figure 4-25: 2D surface plot of tungsten oxide with activation energy of 0.4 eV when melting point temperature was reached in transient state for set D and 250 nanometers thickness.
The 2D surface plot of steady state response for surface plot of tungsten oxide with 0.4 eV activation energy when the melting point temperature was reached at the location of maximum temperature was shown in Figure 4-27 for set D and 250 nanometers thickness.

Figure 4-26: 3D surface plot of tungsten oxide with 0.4 eV activation energy when melting point temperature was reached in transient state for set D and 250 nanometers thickness.

Figure 4-26 was the same plot as Figure 4-25 but in 3D for better understanding. The temperature distribution throughout the considered shape was better studied from 3D...
plot. The applied current was changed to 1.35 mA to get transient response by leaving all other parameters same as that of steady state. It was observed that the melting point temperature was reached in transient state from heat was concentrated at the tip. The material gets melted after reaching the melting point temperature and prevents further current flow. There was no significant difference for tungsten oxide results with the variation in activation energies from 0.3 to 0.4.

**4.18 Results When Input current was modeled as Linear Equation of Time**

![Graph showing temperature variation over time for tungsten oxide, gold, and aluminum](image)

*Figure 4-27: Variation in the temperatures for different values of time when current was modeled as linear equation of time.*
• When current was modeled as function of time no significant difference was
observed in the heat transfer phenomenon with variation of time for any of the
materials gold, aluminum or tungsten oxide.
• The only difference observed was slight variation in the temperatures for different
values of time as shown in Figure 4-27.

4.19 Chapter Conclusions

The amount of currents needed for reaching the melting point temperature for various
dimension sets and thicknesses were reported for gold, aluminum and tungsten oxide.
Melting point temperature was to be reached in transient state for stable gap
formation and better heat distribution for all considered materials. Heat transfer
profiles on the material surfaces were studied and reported. The influence of
considered boundary condition of the hypotenuse of the shape was studied.
Chapter 5

Experimental Verification for Gold

5.1 Overview

A mask was prepared by cutting the required design in the plastic sheet. Gold was vacuum coated on the glass plate in the specified shape using prepared mask. The thickness of the coated gold film was measured with Atomic force microscopy. The current was applied on the gold film tabulating current and voltage values until the gap formation in vacuum with experimental setup. No further current flow would occur after the gap formation.

The voltage current characteristics of the current application process were studied. The microscopic images of the formed gaps suggest the formation of micro channels. The simulation results were verified experimentally.

5.2 Coating Procedure

- A mask was prepared by cutting the required design in a plastic sheet.
- It was held firmly on a glass plate on which gold is to be coated so that it remains in the same position until the completion of coating.
• A cleaned gold wire was placed on the filament.

• The chamber shown in Figure 5-1 was maintained at a vacuum of $10^{-7}$ Torr.

• Current was passed into the filament until the gold wire gets melted and evaporated.

Figure 5-1: Vacuum coating system used for the coating of thin metal films on insulator substrate.
• The evaporated gold gets evenly deposited on the glass plate with mask.

• The coated glass plate shown in Figure 5-2 was cooled to room temperature in the vacuum for prevention of any possible oxidation.

Figure 5-2: Glass plate coated with gold in required shape.

5.3 Thickness Measurement by Atomic Force Microscopy

• The AFM comprises a cantilever with a probe at its end to scan the specimen surface as shown in Figure 5-3 [38,39]

• The sample was mounted on a piezoelectric tube for adjustment of its position.

• When the tip was brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever

• The deflection was measured using a laser spot reflected from the top surface of the cantilever into a photo detector.

• a feedback mechanism was employed to adjust the tip-to-sample distance to maintain a constant force between the tip and the sample.
Figure 5-3: Schematic of Atomic microscopy system showing the optical method of measuring cantilever deflection.

1. Laser.
2. Photo detector.
3. Cantilever.
4. Probe tip.
5. Study surface
6. Piezotube
7. Data processor and feedback electronics
The thickness of the gold film coated on the glass plate was measured with Atomic force microscopy. The value of the thickness in this case was reported to be 43 nanometers with a variance of 5 nanometers for measurements at different surface locations.

Figure 5-4: Top view of the AFM image

In Figure 5-4 the left side portion of the line was gold film and the right side of it was glass plate. Figure 5-5 was the 3D view of the same image.
5.4 Experimental Procedure

The experimental setup as shown in Figure 5-6 comprises a vacuum chamber inside which current was applied on the coated material, a vacuum pump, a DC power supply, connecting cables, 3D manipulator to exactly position the pointers on the coated film. The pointers of two 3D manipulators were exactly positioned on the gold coating as shown.
Figure 5-6: Experimental Setup

1. Vacuum chamber and DC power supply.
2. 3D Manipulators.
3. Vacuum pump.
4. Pointers positioned on metal coating.
The manipulators were connected to the power supply from which the current applied could be varied. The chamber was closed and the air inside was removed with vacuum pump. Electric current was applied on the gold film by gradually increasing the current with power supply until a point when the current suddenly drops to zero. The current value was reported as 160 mA where the gap formation occurs. It was observed that the gap formation was at the centre where the width of the material was least.

5.5 Microscopic Images

Figure 5-7: Microscopic images of considered gold sample. (Magnification 100)

a. before applying current 

b. after gap formation
The images shown in Figure 5-7 were of the sample considered with approximate dimensions of triangular shape $y_0 = 2.05$ mm and $x_0 = 4$ mm respectively whose thickness was measured to be 43 nanometers from atomic force microscopy.

The images shown in Figure 5-8 were of another gold sample where a finer gap was formed but the data for dimensions was not measured.

![Microscopic images of considered gold sample. (Magnification 100)](image)

Figure 5-8: Microscopic images of considered gold sample. (Magnification 100)

a. before applying current  
b. after gap formation

### 5.6 Representative Breaking curves

Representative breaking curves for gold were shown in Figure 5-9. The variation of current and voltage until the formation of gap was plotted in this graph. The current in both the cases increases linearly initially but finally reaches a point where breakage occurs resulting in gap formation and it drops to zero. The current-voltage characteristics in thin film structures presented in [40] were verified.
Figure 5-9: Representative breaking curves for gold

5.7 Verification with Simulated Result.

Table 5.1: Comparison of simulated and experimental Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Experiment (approximate dimensions)</th>
<th>simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>2.05mm</td>
<td>2.05mm</td>
</tr>
<tr>
<td>$x_0$</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>$h$</td>
<td>0.05 mm</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Applied current $i$</td>
<td>160mA</td>
<td>160mA</td>
</tr>
<tr>
<td>Thickness of coated material $T$</td>
<td>48 nanometers (5 nanometer variance)</td>
<td>48 nanometers</td>
</tr>
</tbody>
</table>
When the simulation was carried out with the experimental parameters it was observed that melting point temperature was reached at the tip in transient state. It was also observed that though lesser amount current was needed to reach melting point temperature in steady state it was not easy to control the amount of applied current manually. It could be predicted that fabrication of micro gaps was possible by this approach and is to be investigated further to attain gaps of nano size. There was a need to improve the accuracy of measurement of dimensions of the coated film. The results obtained were reasonable

5.8 Chapter Conclusions

The vacuum coating and experimental procedure were explained. The thickness of the coated sample was measured by atomic force microscopy. The microscopic images of gaps formed experimentally were presented. Representative breaking curves for gold were plotted which suggest that the current increases gradually with voltage until a point and suddenly becomes zero at the point of gap formation. The experimental results for gold were verified with simulated results.
Chapter 6

Conclusions and Future Work

6.1 Conclusions

Electroforming of micro gaps in gold, aluminum and tungsten oxide thin films was investigated in the following study by simulation and experimental research. The heat transfer phenomenon in electroforming process for metals and semiconductors was investigated.

- From simulation the amount of current, dimensions needed for a material could be predicted for the gap formation. For metals gold and aluminum simulation results predicted that melting point temperature was reached in steady state at the tip but heat was distributed over the entire material surface. The heat transfer in the fabrication process has to be transient to avoid heat distribution.

- For tungsten oxide, irrespective of activation energy considered the melting point temperature was reached at the tip. Transient response was preferred even in this case as heat concentration at the tip takes place.

- The simulation results were verified experimentally and representative breaking curves of current application were plotted for gold.
6.2 Future Work

- The simulation was carried out for gold, aluminum and tungsten oxide and should be extended to other materials.

- The micro channel fabrication in gold was investigated successfully the experimentally procedure is to be improved for better results and also to extended other materials.

- A better practice should be implemented for mask preparation and measurement of dimension of coated material. The process of application of current should be improved to avoid experimental errors and also to improve accuracy in readings.

- The controllability of dimensions of formed micro channels is to be investigated experimentally as it would be crucial in their application.
References


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