Crystal growth set-up for Microelectronic process
Jean-Marc Dedulle (iris.dedulle@wanadoo.fr) : IRIS Technologies

Control of geometry + control of power supply = control of thermal gradient

Induction heating modeling of crystal growth set-up
Induction heating model with v4.0

**Geometric Model : Hypothesis**
- 2D cylindrical geometry to obtain optimize coil
- For induction heating model 2D axi

**Physical Model : induction heating**
- Electromagnetic
- Quasi-static approximation ($\sigma \gg \epsilon \omega$) in 2D axi
- Thermal radiation with ambient and in cavity in 2D axi

**Numerical model : strong coupling**
- Vector potential formulation - complex unknown
- Temperature formulation - non linear problem ($T^4, \sigma(T)$) in 3D
- Radiative flux with view factor
Coil Design

Mathematical model: Partial derivative equation

\[ \overrightarrow{A} / \overrightarrow{B} = \text{rot} \overrightarrow{A} \left( \text{flux conservation: div} \overrightarrow{B} = 0 \right) \]

\[ \text{rot} \left( \text{rot} \overrightarrow{A} \right) + j\mu_0 \sigma(T) \omega \overrightarrow{A} = \mu_0 \sigma(T) \text{grad} V \]

2D cylindrical geometry

\[ \overrightarrow{J} = \begin{pmatrix} 0 \\ J_\theta(r,z) \\ 0 \end{pmatrix} \]
Coil Design

In order to design coil we needed losses in the copper Voltage supply and computation of eddy currents in coil

\[ \vec{J}_{\text{total}} = -j\sigma(T)\omega \vec{A} + \sigma(T) \nabla \vec{V} \]

Turn coil are in a serial electric scheme :

\[ I_1 = I_2 \ldots \]

ddp per turn coil imposed : \( \Delta V_i \)

Constraint for an integral property :

\[ I_i = \int_{\partial S_i} \vec{J}_{\text{total}} \cdot d\vec{S}_i \]

Adjustement of \( \Delta V_i \), in order to respect constraint
Physical properties

**Paramètres**

<table>
<thead>
<tr>
<th>Nom</th>
<th>Expression</th>
<th>Valeur</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sigma_isolation</td>
<td>2e3 S/m</td>
<td>2000 S/m</td>
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<tr>
<td>sigma_poudre</td>
<td>1e4 S/m</td>
<td>10000 S/m</td>
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<tr>
<td>ε0</td>
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<td>k_isolation</td>
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<tr>
<td>k_graphite</td>
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<td>k_poudre</td>
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<td>25</td>
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</tr>
<tr>
<td>FREQ</td>
<td>50000 Hz</td>
<td>50000 Hz</td>
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</tbody>
</table>

Frequency = 50 kHz

**Expression**

\[
\sigma_{\text{graphite}} = \frac{7 \times 10^4}{3.5 \times 10^{-4} T + 0.375 + \frac{144.7}{T}} \text{Ω}^{-1} \cdot \text{m}^{-1}
\]
Constraint for an integral property

Single turn domain

\[ I_i = \int_{S} J_{\text{total}} \cdot dS_i \]

\[ J_{\text{total}} = -j\sigma(T)\omega A + \sigma(T) \text{grad } V \]
Single turn domain

ddp per turn coil computed automatically: \( \text{grad} V_i \)

Automatically add to dependent variables:
- \text{emqa.Vtot}_1
- \text{emqa.Vtot}_2
- \text{emqa.Vtot}_3
- \text{emqa.Vtot}_4

Adjustment of \text{emqa.Vtot}_i, in order to respect constraint \( I_0 \)
Radiation flux in cavity

Boundary conditions

\[ T = 80^\circ C \]

\[ -k \nabla T \cdot n = h (T - T_{amb}) + \sigma_s \varepsilon \left( T^4 - T_{amb}^4 \right) \]

Radiation flux in cavity

Non linear system to solve:

\[ \sum_j \left[ \frac{(\delta_{ij} - (1 - \varepsilon_j) F_{ij})}{\varepsilon_j} \right] \phi_j = \sum_j (\delta_{ij} - F_{ij}) \sigma_s T_j^4 \]

View factor:

\[ F_{ij} = \frac{1}{\pi S_i S_j} \int_{S_i} \int_{S_j} \frac{\cos \beta_i \cos \beta_j}{d_{ij}^2} dS_i dS_j \]
Radiation flux in cavity

opaque
Caution to mesh: Skin effect are very important in copper
Solve

Electromagnetism

Heat transfer
Post-processing

Joule losses
Graphite & Insulation

Exercise → Compute electrical parameters: R and L
Post-processing 3D

Joule losses in graphite and insulation

T in °C