Thermal Performance Assessment of Tungsten Based Magneto-Resistive Heat Switch for Space Application

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Abstract

Heat switches are generally used for regulating heat flow. These heat switches are categorized as mechanical and magneto-resistive heat switches. Among these, a magneto-resistive heat switch (MRHS) is used for controlling the heat flow at a very low temperature of below 10 K. Because of this advantage, it is implemented in space applications for controlling heat flow across thermally conductive material. Therefore, in the present study, by choosing MRHS, an analytical investigation is carried out for assessing the thermal performance at a very low temperature of below 10 K. Here, tungsten is used as a magneto-resistive material (MRM). Initially, an analytical model is developed for evaluating the thermal performance of MRHS. The created model was then evaluated using experimental data from the literature by selecting thermal conductivity, thermal conductance, and switching ratio as performance characteristics. From the validation analysis, it is found that the developed model has a reasonable agreement with experimental data and observed a maximum allowable error of $\pm$ 8.3%. Later, the developed model has been used for investigating the performance of MRHS. The inlet parameters chosen for the performance evaluation are magnetic field (MF) and MRM temperature. By observing the numerical results obtained based on the developed numerical model, it is found that for a given MRM temperature of 5 K and by varying the MF from 0.1 T–2 T, the thermal conductance increases linearly by 150%, the thermal conductivity decreases logarithmically by 97%, and switching ratio increases logarithmically by 99%, respectively. Further, it is realized that the developed model procedure can be adopted for assessing the thermal performance of different heat switches that are used for space applications.

Keywords: Magnetic field, Low temperature, Switching ratio, Magento-resistive material, Analytical model.

1. Introduction

Cryogenic heat switches are the key components of many spaces applications and low-temperature systems. The flow of heat is controlled by the heat switches between two contact surfaces. The majority of thermal switches that function in spacecraft temperature ranges are passively actuated devices that self-regulate their conductance without the assistance of any controller inputs. Heat switches offer thermal insulation as well as the connection between various system components. In its off state, an ideal heat switch provides full thermal insulation and provides strong thermal coupling when turned on.

The heat switches are broadly classified into mechanical [1,2], gas-gap, superconducting, and magneto-resistive types. Thermal conductivity of a mechanical heat switch is proportional to contact between two surfaces, whereas the thermal conductivity of a Gas-Gap heat switch [3-6] is proportional to the presence or absence of gas between two interlocking pieces. In a Superconducting heat switch [7,8], phase transition reduces thermal conductivity but, in a Magneto-resistive heat switch [9-13], the application of an external magnetic field reduces the electronic contribution to thermal conductivity. It is used to get almost complete isolation in its off state by applying a magnetic field. This paper deals with the working principle of Magnetoresistive heat switches (MRHS), in presenting a broad overview to assess the thermal performance of Magneto-resistive heat switches at different temperatures (2.5-10 K) and different magnetic field values (0.1-2 T).

In the field of space, heat switches are applied to control the flow of heat. The 'ON' state (closed switch) has a large value of thermal conductivity but has to control thermal conductivity in the 'OFF' state (open switch) condition. In a Magnetoresistive heat switch, metal is placed inside an external applied magnetic field. Due to Lorentz's force [21], electrons take a helical path, thus increasing the resistivity of a metal, states that thermal conductivity of Magnetoresistive material changes in the vicinity of a strong magnetic field. It is best to use in the space applications to get complete isolation in the 'OFF' state.

Figure 1. Magnetoresistive heat switch [9,10].

After a wide range of literature surveys, it was observed that for predicting the performance of thermal conductivity in magnetoresistive heat switch for tungsten material, thermal conductivities of high purity single crystal tungsten at temperature range of 1.5-6 K were often reported in the literature [9-10]. Further, several researchers investigated the thermal performance experimentally with help of correlations [11-14], and some researchers have calculated thermal conductivity tensor for different materials [15-19], but no one calculated the thermal conductivity tensor for tungsten material for MRHS. Some researchers used both steady and transient approaches. Temperature gradients and heat input are measured using the steady-state approach. The transitory approach, on the other hand, measures the temperature decrease over a brief period of time. In comparison to transient methods, steady-state methods have a longer waiting period, and reliable detection of heat and minor temperature variations is challenging. It was found that none of them developed an analytical model for MRHS thermal performance prediction. To overcome these challenges conductivity tensor is developed to solve the thermal performance for Tungsten based Magnetoresistive heat switch. To find the accurate solution of tensor, Gauss Elimination method is used.
Thus, in the present investigation, thermal conductivity for tungsten material is analyzed by implementing the Gauss Elimination approach at different temperature ranges and the magnetic field value.

2. Analytical model for MRHS thermal performance prediction

To calculate the thermal performance of heat switches at a very low temperature, it is needed to calculate thermal conductivity on three mutually perpendicular planes (x, y, and z-face) and in each x, y, and z-direction. Conductivity does not follow vector law of addition because it has magnitude, direction, and plane. To get overall thermal performance, a conductivity tensor [21] is developed. E.g.- the scaler is a zero-order tensor because it is only having magnitude, the reason behind vector being a first-order tensor is because it has magnitude and direction whereas conductivity is a second-order tensor with magnitude, direction, and a plane. A developed mathematical model is used to determine the thermal performance of tungsten based MRHS.

2.1. Model equations

Conductivity in X, Y, and Z-axis,

$$\kappa_x = \kappa_{xx} + \kappa_{xy} + \kappa_{xz} \quad \text{(Eq. 1)}$$

$$\kappa_y = \kappa_{yx} + \kappa_{yy} + \kappa_{yz} \quad \text{(Eq. 2)}$$

$$\kappa_z = \kappa_{zx} + \kappa_{zy} + \kappa_{zz} \quad \text{(Eq. 3)}$$

The overall thermal performance from the conductivity tensor (Eqs. 1–3) to a matrix form can be written as,

$$\begin{pmatrix} \kappa_x \\ \kappa_y \\ \kappa_z \end{pmatrix} = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} & \kappa_{xz} \\ \kappa_{yx} & \kappa_{yy} & \kappa_{yz} \\ \kappa_{zx} & \kappa_{zy} & \kappa_{zz} \end{pmatrix} \quad \text{(Eq. 4)}$$

The dilemma of the fact whether the conductivity tensor is a symmetric one or not can be cleared in the following way. A tensor is characterized by nine parameters that can be split into a symmetric and an antisymmetric (skew) tensor. The symmetrical part of a tensor is denoted as follows,

$$\kappa_{xy} = \kappa_{yx},\ \kappa_{xz} = \kappa_{zx},\ \kappa_{yz} = \kappa_{zy} \quad \text{(Eq. 5)}$$

Only six independent parts make up the symmetric tensor, which represents true extension or contraction along the three primary coordinate axes. A sphere can be transformed into an ellipsoid using the six terms. Keeping the primary axis constant with the three angles and the length of the three principal axes with another three terms, named as K_{xx}, K_{yy}, and K_{zz}, yields the transformation. The anti-symmetrical part of the tensor is denoted as follows,

$$\kappa_{xx} = \kappa_{yy} = \kappa_{zz} \quad \text{(Eq. 6)}$$

$$\kappa_{xy} = -\kappa_{yx},\ \kappa_{xz} = -\kappa_{zx},\ \kappa_{yz} = -\kappa_{zy} \quad \text{(Eq. 7)}$$

Now, the final conductivity tensor comes in the form of:

$$\kappa = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} & \kappa_{xz} \\ -\kappa_{xy} & \kappa_{yy} & \kappa_{yz} \\ -\kappa_{xz} & -\kappa_{yz} & \kappa_{zz} \end{pmatrix} \quad \text{(Eq. 8)}$$

when a magnetic field is applied externally in the z-direction as shown in Figure 2, the Lorentz force acts on the electrons within the metals, causing the Magnetoresistive effect to occur, and Fleming's left-hand rule [22] can be used to determine the direction of a force.

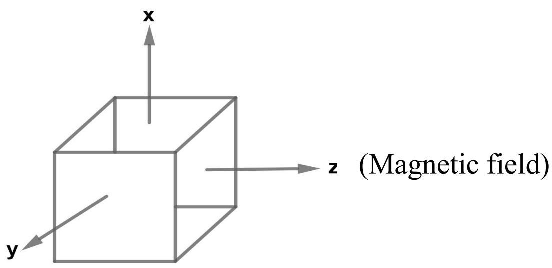

Figure 2. Finite element (tungsten material) represents magnetic field in the z-direction.

If the flow of electrons is in the x, y and z direction respectively, and the applied field in the z direction, then force on the moving charged particle will be in an inward, upward, and zero respectively, the force acting on a moving charged particle is,

$$F = q(v * B) \quad \text{(Eq. 9)}$$

$$F = qvB\sin\Theta \quad \text{(Eq. 10)}$$

where F denotes force (N), q is an electric charge (coulomb, C), v signifies velocity (m/s), and B represent magnetic field (Tesla). From equation (10), it is observed, if the angle between current and magnetic field is 90^0, maximum force can be achieved and if the angle between these is zero then force acts on moving charged particle inside the magnetic field will be zero. This study concludes, the plane of the magnetic field should be normal to the direction of flow of electrons.

In this study, tungsten material is isotropic, and electrons will take a helical orbit in the plane perpendicular to direction of magnetic field applied after being exposed to it (i.e., $Ꝁ_{xx} = Ꝁ_{yy}$). Here, neglects the heat flow in z direction ($K_{zz} = 0$) because it is not possible to control the heat flow in z direction. Heat is transferred through metals by free-electron diffusion and phonon (lattice) propagation. At cryogenics temperature [10], thermal conductivity (Ꝁ) is the summation of the above factors:

$$\kappa(T) = \kappa_e(T) + \kappa_g(T) \quad \text{(Eq. 11)}$$

where $Ꝁ_e T$ the electronic conductivity, $Ꝁ_g T$ is the lattice/phonon conductivity, where both being dependent on temperature (T). A large thermal Magnetoresistive effect is known to exist in metals with a confined Fermi surface. Gallium, Cadmium, Tungsten, and Beryllium are among the metals that meet these requirements.

Finally, the overall conductivity tensor came in the form of:

$$\kappa = \begin{pmatrix} \kappa_{xx} & \kappa_{xy} & 0 \\ -\kappa_{xy} & \kappa_{xx} & 0 \\ 0 & 0 & \kappa_{zz} \end{pmatrix} \quad \text{(Eq. 12)}$$

$$\kappa_{xx} = \kappa_g + (\kappa_e)_{xx} \quad \text{(Eq. 13)}$$

$$\kappa_{xy} = \kappa_g + (\kappa_e)_{xy} \quad \text{(Eq. 14)}$$

In the case of a closed Fermi surface, the tensor elements $(\kappa_e)_{xx}$ and $(\kappa_e)_{xy}$ are closed at high fields according to semi-classical magnetoresistance theory [9], and they follow the below-mentioned form asymptotically:

$$(\kappa_e)_{xx} = \delta_{xx}(T) / B^2 \quad \text{(Eq. 15)}$$

$$(\kappa_e)_{xy} = L_0\tau(n_e - n_h)ec / B + \delta_{xy}(T) / B^3 \quad \text{(Eq. 16)}$$

where $L_o = 2.44 \times 10^{-8} W\Omega / K^2$ is Lorenz number [20], τ is electronic relaxation time, B signifies magnetic field, e represents electronic charge, n_e denotes the number of electrons, and n_h denotes the number of holes, $\delta_{xx}(T)$ and $\delta_{xy}(T)$ are the variables that depend on temperature and are determined by the scattering phenomenon of the metals,

$$\kappa_{xx} \approx \kappa_g(T) + \delta_{xx}(T) / B^2 \quad \text{(Eq. 17)}$$

$$\kappa_{xy} \approx \kappa_g(T) + \delta_{xy}(T) / B^3 \quad \text{(Eq. 18)}$$

The type of the scattering influences the temperature-dependent phonon conductivity component Ꝁg(T). It is believed that the following scattering mechanisms exist, they are,

(A) Boundary scattering.

(B) Normal three-photon processes.

(C) Impurity scattering.

$$\kappa_{xx} = PT^n + \delta_{xx}(T) / B^2 \qquad \text{(Eq. 19)}$$

$$\kappa_{xy} = PT^n + \delta_{xy}(T) / B^3 \qquad \text{(Eq. 20)}$$

where P is the coefficient of phonon conductivity and n can have a value of 2 or 3. Let the scattering of the dislocation or the electrons limits the phonon current, then consider a T^2 relationship, on the other hand, while boundary scattering limits the phonon current, then consider a T^3 relationship.

$$\delta_{xx} / T = \phi_o + \phi_3 T^3 = \delta_{xy} / T \qquad \text{(Eq. 21)}$$

$$\delta_{xx} / T = \phi_o + \phi_3 T^4 = \delta_{xy} / T \qquad \text{(Eq. 22)}$$

$\delta_{xx}(T)$ and $\delta_{xy}(T)$ follow a Wiedemann-Franz law [8, 23], if scattering is elastic then it follows equation (21) otherwise follows equation (22), where ϕ_0 and ϕ_3 are constants having value 0.42 and 0.0063 respectively.

3. Validation

Validation is the process of comparing the results obtained from the analytical solution of the thermal conductivity tensor with the experimental results available in the literature. In this study, the results of the thermal conductivity (Ꝁ) of tungsten based MRHS at very low-temperature are validated with the experimental results. After finding the close approximation of results obtained analytically with the experimental result, this model shows the feasibility to plot different results.

3.1. Validation of thermal conductivity and switching ratio

In this study, the tungsten based Magnetoresistive based heat switch is preferred because of its high switching ratio. At a given magnetic field value, strong thermal conductivity in the 'ON' state and low thermal conductivity in the 'OFF' state. This overall thermal conductivity which is the addition of phonon and electronic thermal conductivity and switching ratio shows appreciable results for the practical application.

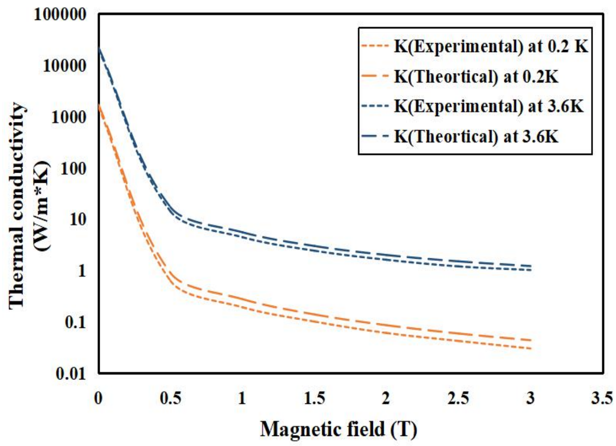

Figure 3. Validation of data amidst the developed model and the experimental data available in the literature.

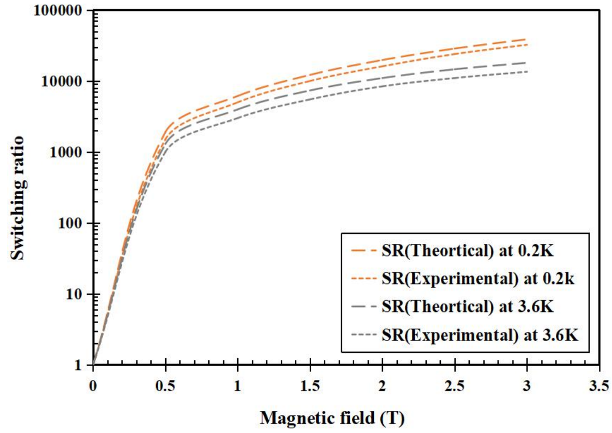

Figure 4. Validation of data amidst the developed model and the experimental data available in the literature.

A comparison is done between the experimental data and predicted data to assess the dependability of the established analytical technique in the literature [11] of thermal conductivity and switching ratio as a function of the magnetic field at different temperatures. Figure 3 and Figure 4 show the validation of the thermal conductivity and switching ratio by varying the magnetic field. From Figure 3 and 4 results are validated, and The proposed technique is found to be reliable, with a maximum probable inaccuracy of $\pm$5.67 %. Further, it is found in Figure 3, that with the increase in the magnetic field value, the thermal conductivity is decreasing because electronic conductivity is decreasing due to the action of Lorentz force and in Figure 4, it is found that increasing the magnetic field 'OFF' state, the thermal conductivity decreases due to which switching ratio increases.

4. Results and discussion

The developed analytical model of tungsten-based Magnetoresistive heat switches for overall thermal conductivity and switching ratio at a very low temperature (2.5 K - 10 K) at different magnetic field values (0.1-2 T) shows a good approximation with the experimental results. Thus it motivates to analyze more results to know the behavior of ON state thermal conductivity and OFF state thermal conductivity at different temperatures and magnetic fields.

4.1. Tungsten MRHS

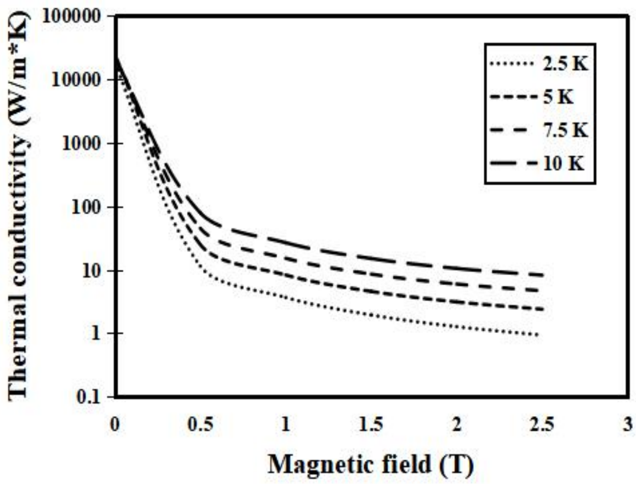

Figure 5. Measured thermal conductivity as a function of Magnetic field in "ON" and "OFF" state conditions for different temperature values.

In the absence of a magnetic field (zero magnetic field), 'ON' state thermal conductivity ($Ꝁ_{on}$) is achieved, and to get 'OFF' state thermal conductivity ($Ꝁ_{off}$) magnetic field is applied normal to the direction of heat flow. From Figure 5, it is understood that in 'ON' state thermal conductivity is very high due to contribution of both electronic conductivity and phonon conductivity. In 'OFF' state, the contribution of electronic conductivity vanishes due to effect of magnetic field so that overall thermal conductivity decreases, and switching ratio increases as shown in Figure 6.

As temperature increases in 'ON' state condition, initially overall thermal conductivity will increase due to an increase in both phonon and electronic conductivity but after a certain value as temperature increase, phonon conductivity increases which suppresses electronic conductivity means overall thermal conductivity will decrease, and in 'OFF' state as temperature increases, current increase due to this magnetic force increase. The high value of force resists the electronic thermal conductivity and phonon conductivity increases mean overall thermal conductivity increases.

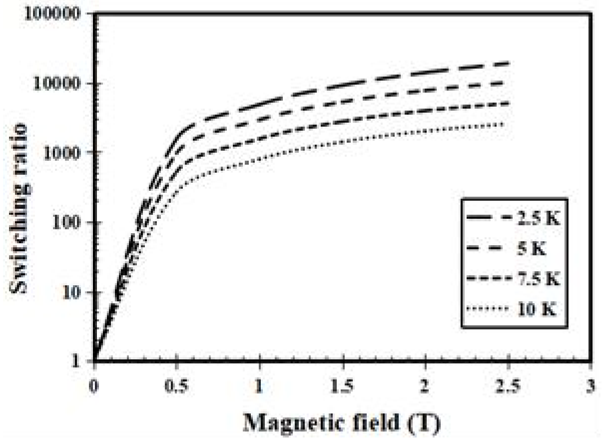

Figure 6. Measured switching ratio as a function of Magnetic field in "ON" and "OFF" state conditions for different temperature values.

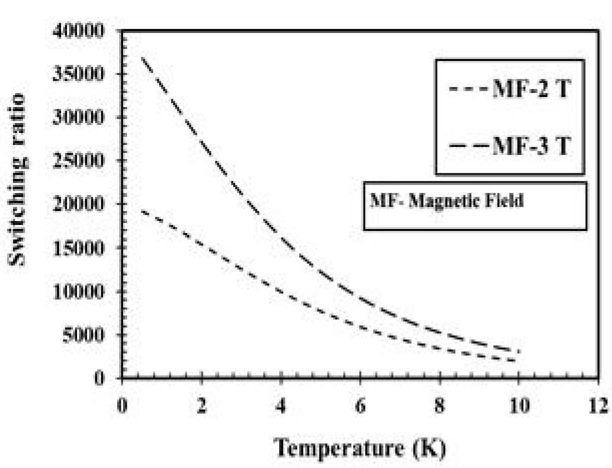

Figure 7. Measured Switching ratio as a function of temperature at a magnetic field value of 2T and 3T.

From Figure 7, it is observed that switching ratio decreases as temperature increases. This happens because, with increase in magnetic field, the electronic conductivity is almost negligible and as temperature increases, phonon conductivity increases due to scattering phenomena. So, in the 'OFF' state, as temperature increases, off-state thermal conductivity increases which decreases switching ratio.

5. Conclusions

The measured thermal conductivity for tungsten materials in both 'ON' and 'OFF' state where the former refers to zero magnetic field (high thermal conductivity) and the latter refers to an applied magnetic field (0.1 – 2 T), and it seems at different temperatures (2.5 – 10 K).

The major conclusions drawn from the impact of thermal assessment for tungsten-based magneto-resistive heat switches are drawn as follows:

- Developed Gauss Elimination method-based analytical tool for performance prediction of magneto-resistive heat switch (MRHS) at low temperature.
- Analyzed MRHS performance at different magnetic fields and temperatures.
- Assessed MRHS performance for pure single-crystal Tungsten material.
- From this study, Magnetoresistive heat switch has a high switching ratio when the temperature is very low.
- 'OFF' state thermal conductivity has a very less value when temperature is very less.
- The thermal conductance increases linearly moving from 'on' to 'off' state by 150%.
- The thermal conductivity decreases logarithmically moving from 'on' to 'off' state by 97%.
- Switching ratio increases logarithmically by 99% from 'on' to 'off' state because by increasing magnetic field value off conductivity decreases.

The results of switching ratio and thermal conductivity for tungsten-based Magneto resistive heat switches are obtained by developing a conductivity tensor using Gauss Elimination method. Further, it is found that the developed model procedure can be adopted for assessing the thermal performance of different heat switches that are used for space applications.

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