

MAGNETOMECHANICAL THERMAL DIODE WITH TUNABLE SWITCHING TEMPERATURES

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Abstract: We develop a device concept for thermal diodes with mechanically tunable switching temperatures by exploiting the temperature dependence of the magnetization of ferromagnetic materials. A coupled thermo-mechanical model is used to examine one potential implementation of our concept, which exhibits unique thermal characteristics analogous to that of constant-current electrical diodes. Such thermal diodes may play an important role in synergistic integration of thermal energy storage and harvesting devices for time-varying heat sources.

Keywords: Thermal switch; Thermal diode

INTRODUCTION

Reconfigurable thermal networks enabled by functional thermal devices can play a key role in robust and efficient thermal control [1-3] and allow synergistic integration of thermal energy storage and harvesting devices. Several designs of functional thermal devices have been developed. Electrostatic devices that can modulate the thermal conductance of suspended microstructures have been reported [4], as well as thermal switches that use differential thermal expansion or first-order phase transition to open and close heat conduction paths [5,6]. One drawback of these devices is that the switching temperatures are fixed by specific materials and cannot be readily tuned.

We report a device concept for thermal diodes that exploits the temperature dependent magnetization of a ferromagnetic material. A coupled thermo-mechanical model is used to examine one potential implementation, which shows that the device exhibits a unique characteristic analogous to that of constant-current diodes. Its switching temperatures can be readily set simply by tuning mechanical parameters. Potential applications, as well as limitations of our device concept, are also discussed.

ANALYSIS AND SETUP

Fig. 1 shows a thermal diode that consists of a ferromagnet, a hard magnet, and a linear spring of stiffness k . The top surface and the hard magnet (bottom surface) are separated by distance L_t . The top surface is mechanically biased by the amount $L_t - L_g$, so that a finite spring force acts on the ferromagnet when it contacts the top surface. A previous study examined a similar device for thermal energy harvesting applications [7].

The ferromagnet transports thermal energy between the surfaces when the hot bottom surface is

maintained at temperature above a threshold value, T_{up} , and the cold top surface is maintained at temperature below a threshold value, T_{down} (forward bias). When the top surface is hotter than the bottom, the ferromagnet does not oscillate. Under this reverse bias condition, there is no thermal energy transport across the gap except through thermal leakage via heat conduction along device frames or radiation.

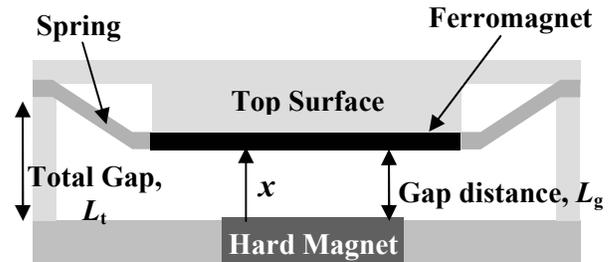


Figure 1: Schematic of thermal diode. Ferromagnet is in contact with the cold top surface ($x = L_g$).

The threshold temperatures, T_{up} and T_{down} , are determined by a balance between the spring force and magnetic force F_{mag} :

$$kL_t = F_{mag}(x = 0, T = T_{up}) \quad (1)$$

$$k(L_t - L_g) = F_{mag}(x = L_g, T = T_{down}) \quad (2)$$

The temperature dependence of F_{mag} arises primarily from the temperature dependence of the ferromagnet magnetization. The x dependence of F_{mag} is governed by the geometry and magnetic properties of the ferromagnet, hard magnet, and surrounding structures.

When the ferromagnet temperature is below T_{down} , the magnetic force exceeds the spring force and the ferromagnet moves to contact the bottom surface. Thermal energy is transferred from the bottom surface

to the ferromagnet until its temperature reaches T_{up} and the magnetic force falls below the spring force. The excess spring force causes the ferromagnet to detach from the bottom surface and brings it to the top surface. The ferromagnet then cools down by heat transfer until its temperature falls below T_{down} . The process then repeats, creating oscillatory motion of the ferromagnet between the two surfaces.

As an example, we consider a prototype device that consists of a Gd foil (6 mm x 6 mm x 120 μ m) and a commercially available NdFeB hard magnet (diameter 6.5mm, thickness 3mm) [7]. Fig. 2 shows experimentally measured magnetic force on the Gd as a function of temperature, which is consistent with the magnetization versus temperature data reported in the literature [8].

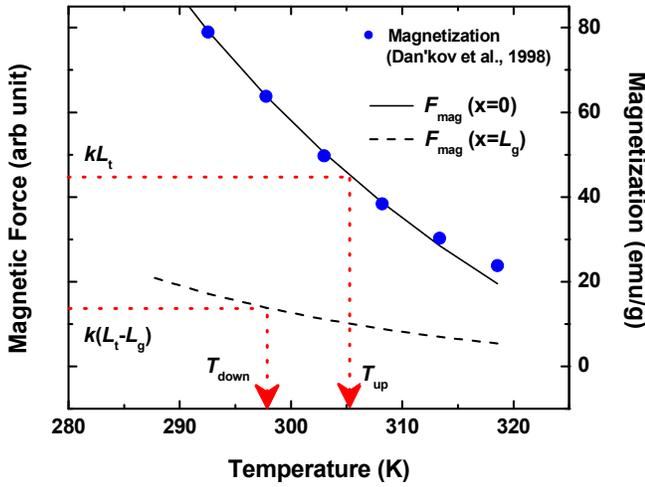


Figure 2: Temperature dependence of the magnetic force [7] (left axis) and the experimentally measured magnetization [8] on the Gd foil (right axis). The two threshold temperatures T_{up} and T_{down} are determined from the force balance.

Fig. 2 also shows a determination of T_{up} and T_{down} for one set of arbitrarily chosen parameters, k , L_t , and L_g via Eqs. (1-2). By simply changing these parameters, we can tune the threshold temperatures of the device.

A key metric of the present thermal diode is the mechanical oscillation frequency as it determines the magnitude of the on-state thermal current. When the mechanical resonance frequency is sufficiently high, the ferromagnet frequency is limited primarily by the rate of heat transfer between the ferromagnet and the top/bottom surface. The latter is limited by thermal contact resistance per unit area, R_{th} [4].

In order to quantitatively analyze the diode characteristics, we numerically solve the equation of motion together with the lumped thermal capacitance model to determine the position x and the temperature T of the ferromagnet as a function of time:

$$m \frac{d^2 x}{dt^2} = k(L_t - x) - F_{mag} \quad (3)$$

$$\rho d c_p \cdot \frac{dT}{dt} = (T_{hot/cold} - T) / R_{th} \quad (4)$$

The lumped capacitance model assumes that temperature non-uniformity within the ferromagnet is negligible. This is valid when the thickness of the ferromagnet d is small (of the order of 100 μ m or less) so the Biot number is much smaller than unity [9].

Eqs. (3) and (4) are coupled via the temperature dependence of F_{mag} . Heat conduction through air and radiation are assumed to be negligible compared with direct heat transfer across solid-solid contacts. The specific heat of Gd, c_p , varies with temperature and magnetic field [8,10], which has been taken into account in the model. $T_{hot/cold}$ is the temperature of either the bottom (hot) or top surface (cold) depending on which surface the ferromagnet is contacting.

RESULTS AND DISCUSSION

We validate our model by comparing the previously measured [7] oscillation frequency with our prediction (Fig. 3). The cold and hot surface temperatures were fixed at $T_{cold} = 0$ $^{\circ}$ C and $T_{hot} = 50$ $^{\circ}$ C. The total gap, L_t , was 1.6 mm and L_g was varied. The spring constant was 200 N/m. Frequency increases with decreasing L_g because stronger magnetic force at the top surface (the top surface is closer to the hard magnet) leads to higher T_{down} and hence shorter cooling time. The predicted frequency values agree well with the experimental data for a thermal contact resistance of $R_{th} = 1.5 \times 10^{-3}$ m^2 K/W. Such large contact resistance is a result of significant surface roughness (> 5 μ m) of the Gd and NdFeB samples and is consistent with results from our independent thermal contact resistance measurement.

We next discuss representative thermal diode characteristics we predict using the model. Our goal is to highlight salient features of the thermal diode. We set $R_{th} = 10^{-3}$ m^2 K/W and $L_t = 1.6$ mm. We fix T_{cold} at 0 $^{\circ}$ C, but vary T_{hot} from 0 to 250 $^{\circ}$ C. The Curie temperature of Gd is approximately 20 $^{\circ}$ C. Gap distance L_g is again varied.

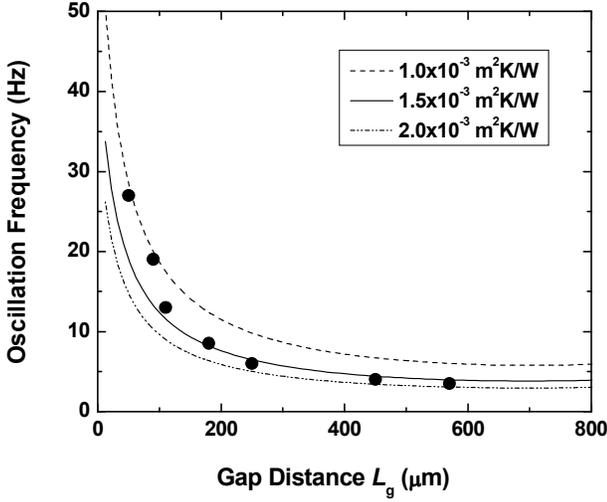


Figure 3: Oscillation frequency of the ferromagnet in the prototype device: experimental data (symbol) [7] and model prediction (lines) for three different values of thermal contact resistance.

When $T_{\text{hot}} < T_{\text{up}}$, the thermal diode is in the off state and the oscillation frequency is zero. When T_{hot} exceeds a threshold value, the frequency increases rapidly with increasing T_{hot} and then approaches a plateau for sufficiently high values of T_{hot} . This can be explained by analyzing heating/cooling of the ferromagnet. One can show by solving Eq. (4) that the cooling and heating time of the ferromagnet are:

$$t_{\text{cooling}} = \rho dc_p R_{\text{th}} \ln \frac{T_{\text{up}} - T_{\text{cold}}}{T_{\text{down}} - T_{\text{cold}}} \quad (5)$$

$$t_{\text{heating}} = \rho dc_p R_{\text{th}} \ln \frac{T_{\text{hot}} - T_{\text{down}}}{T_{\text{hot}} - T_{\text{up}}} \quad (6)$$

The heat transfer limited oscillation frequency is then $f_{\text{heat}} = 1/(t_{\text{cooling}} + t_{\text{heating}})$. The initial rapid increase in frequency comes from decrease in t_{heating} with increasing T_{hot} . When T_{hot} is sufficiently high, f is limited primarily by t_{cooling} and mechanical transit time. No further increase in f is therefore observed with further increase in T_{hot} , seen in Fig. 4.

The cycle averaged thermal current q_{device} across the diode per unit area is equal to the product of the frequency f and the energy transported per cycle E . The latter can be calculated as the net change in thermal energy of the ferromagnet per cycle: $E = \rho dc_p (T_{\text{up}} - T_{\text{down}})$. Since E is independent of T_{hot} , the quantity q_{device} follows an almost identical trend as the frequency f . That is, for a fixed value of T_{cold} , q_{device} increases sharply near the turn-on hot surface temperature but saturates at higher values of T_{hot} . Such

unique characteristic is analogous to that of constant-current electrical diodes.

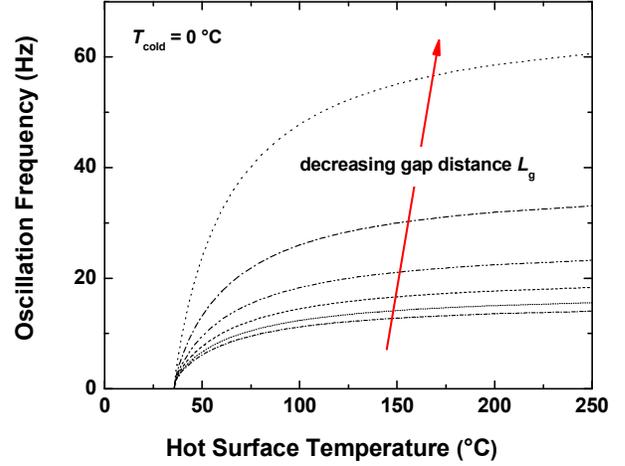


Figure 4: Predicted oscillation frequency as a function of hot surface temperature for different values of gap distance, L_g .

In the heat transfer-limited regime, the saturation value of q_{device} is approximately given as

$$q_{\text{device}} \approx \frac{T_{\text{up}} - T_{\text{down}}}{R_{\text{th}} \ln \frac{T_{\text{up}} - T_{\text{cold}}}{T_{\text{down}} - T_{\text{cold}}}} \quad (7)$$

The maximum thermal current is therefore limited primarily by the thermal contact resistance. High on-state thermal current can therefore be achieved by improving thermal interfaces between the ferromagnet and the top/bottom surfaces. Threshold temperatures, T_{up} and T_{down} (hence mechanical design of the device), have much smaller effects as they appear in both the numerator and the denominator. This can be seen in Fig. 5 where there are only small differences in thermal current for different gap distances. The thermal current does not depend strongly on the thickness and heat capacity of the ferromagnet as their effects on f and E cancel each other.

Reliable, low-resistance thermal interfaces between the ferromagnetic element and hot/cold surfaces are critical for successful performance of the present thermal diode. Direct solid-solid contacts require significant loading pressures for low contact resistance and may introduce fracture, cold-welding, and other reliability challenges. Previous studies [11,12] demonstrated liquid-based reliable and reversible thermal interfaces with low thermal contact resistances, which can be incorporated into our thermal diode.

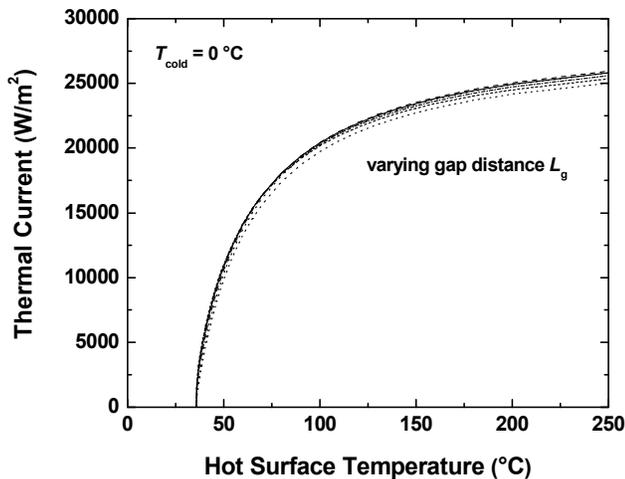


Figure 5: Predicted q_{device} as a function of hot surface temperature for different values of gap distance, L_g .

The constant thermal current diode is well-suited for hybrid solar-thermal energy harvesting/storage systems (e.g., photovoltaic cells combined with a phase-change storage medium and a thermoelectric element) because it helps maintain constant and sustained power generation. The diode turn-on/off temperatures can be tuned by changing mechanical parameters, such as L_g and spring constant. In principle, gap spacing can be tuned *in situ*, for example, using a built-in actuator. This is a potential advantage over thermal switches based on phase change or shape memory effects where switching temperatures are fixed by material properties. Because our thermal diode relies on oscillatory motions of a ferromagnetic element and intermittent contacts, however, it may not be suited for precise temperature control of devices that are susceptible to mechanical vibration or devices with small thermal mass.

CONCLUSION

We report a new device concept for thermal diodes that exploits the temperature dependence of the magnetization of ferromagnetic materials. We solve a coupled thermomechanical model to elucidate the characteristics of the device. Our model is validated using experimentally measured oscillation frequency of a ferromagnetic element in a prototype device. The present thermal diode exhibits a unique thermal characteristic analogous to constant-current electrical diodes. The diode switch-on temperature can be readily tuned by changing the mechanical parameters of the device.

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