Tunable, passive thermal regulation through liquid to vapor phase change

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ABSTRACT
The increasing complexity and power density of electronic systems have necessitated the development of thermal circuits that can not only remove but actively redirect the flow of heat. Passive thermal regulators are promising as heat routing components that can mitigate large temperature spikes by transitioning between high and low resistance states without external actuation. Existing regulators, however, are often either limited to fixed temperature regulation ranges due to solid-state material property limitations or are difficult to package in a compact form factor. Here, we present a passive, compact (1/21 cm2 active area), and tunable thermal regulator that functions based on the dynamics of vapor transport through a noncondensable gas cavity. The device demonstrates a switching resistance ratio of 4 in response to variations in the input power ranging from approximately 0.6 W to 14 W. The device is also able to set the temperature difference across the hot and cold sides to a fixed, “clamped” value that is reasonably independent of heat flow. Both the overall resistance and the clamped temperature difference can be easily tuned by presetting the pressure of the noncondensable gas. We present a brief analysis of the physical operating principles of the device and lay the groundwork for the development of future passive and tunable thermal circuitry components.

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The ability to route heat analogously to electricity is a compelling concept with promising applications in various space-constrained, power dense systems. Conventional thermal management solutions targeting merely heat dissipation are nonoptimal for systems with spatially nonuniform and highly transient heat generation.1,2 These systems can benefit from the addition of nonlinear, switchable thermal components for temperature regulation,3 heat flow inversion,4,5 and thermal isolation.6,7 The current library of such components available to researchers includes thermal switches, diodes, and regulators.6,8–13 Passive components requiring no external input power are particularly useful and promising. Solid-state devices have leveraged metal-insulator phase transitions14 or thermal expansion induced flexing15 to switch effectively between high thermal resistance “off” states and low thermal resistance “on” states. These devices, however, are often limited to fixed temperature regulation ranges tunable only through permanent procedures such as doping16 or may experience mechanical fatigue after repeated deformation.17 Liquid-vapor phase change is a relatively tunable, nonlinear thermal process that can be harnessed for thermal regulation.18–20 One challenge, however, is packaging the devices in a compact form factor that can be easily integrated with existing electronic systems. Variable conductance heat pipes, for instance, are highly effective temperature regulators but require a large condenser area to function, limiting their use to large-scale devices such as Stirling engines.21

In this work, we present a passive, tunable thermal device that utilizes vapor transport in a noncondensable gas (NCG) cavity to achieve a switchable thermal resistance in response to varying levels of heat flow. Compared to existing liquid-vapor phase change regulators, the device is relatively compact with an active working area of 1 × 1 cm2. In addition to a switchable resistance, the device is able to clamp the hot and cold sides to a heat flow independent temperature difference. The resistance switching and clamped temperature difference, ΔTc, are tunable based on the pressure of the NCG. We assess the effectiveness of our device in terms of a conventional switching ratio metric, as well as a nonlinearity coefficient, βc, which evaluates the strength of the ΔT clamping.
Figure 1(a) shows a cross-sectional schematic highlighting the working principles of the device. The device is composed of two pieces of silicon bonded to a Pyrex insert to form a 500 µm thick cavity. Pyrex is utilized in order to reduce parasitic heat conduction outside of the active phase change region. A 1 x 1 cm² serpentine thin-film platinum resistor is patterned onto each side of the device and serves simultaneously as a heater and a resistance temperature detector (RTD) during the experiments. Micropillar arrays are etched into the silicon by ultraviolet laser ablation to form porous wicks [Fig. 1(b)], and the chamber is filled with a mixture of de-ionized water and NCG (overall fabrication and charging details are given in the supplementary material). As water in the heated wick evaporates, the vapor is driven through the NCG and condenses on the cold side. The liquid then recirculates to the hot side through capillary action via grooves etched into the insert sidewalls [Fig. 1(c)]. The NCG acts as a diffusion barrier to the vapor transport and has an equivalent thermal resistance, $R_{NCG}$, which varies based on the pressure of the NCG, $P_{NCG}$, as well as the temperature difference between the hot and cold sides, $\Delta T$. As $\Delta T$ increases, the vapor mass fraction gradient also increases and has a non-linear effect on the vapor transport, reducing $R_{NCG}$. Figure 1(d) shows the resistance stack in the active phase change region of the device, which includes the micropillar wick resistances ($R_{w,h}$ and $R_{w,c}$) and liquid-vapor interfacial resistances ($R_{w,h}^{D}$ and $R_{w,c}^{D}$) in series with $R_{NCG}$. Parallel heat conduction occurs through the cavity sidewalls ($R_{p}$).

The effective thermal resistance across the device is defined as $R_{th} = \Delta T/Q$, where $\Delta T$ is calculated as the difference in the area-averaged temperatures of the hot and cold sides, $T_{h,avg} - T_{c,avg}$ and $Q$ is the total heat input. The uncertainty in the experimentally measured temperature using the calibrated heaters as RTDs ranges from approximately ±0.4°C to ±0.7°C (the details are given in the supplementary material). During experiments, $Q$ is incremented steadily to one heater with a DC power supply, while the other side of the device is cooled with a cold plate. The heat flow rate $Q$ is limited in each experiment to approximately 14 W to prevent degradation of certain experimental components above 95°C (the details are given in the supplementary material).

The device was characterized at four different NCG pressures of $P_{NCG} < 0.1$ kPa and $P_{NCG} = 12$ kPa, 23 kPa, and 34 kPa. $R_{th}$ for each $P_{NCG}$ is plotted vs $Q$ in Fig. 2. For the baseline case of $P_{NCG} < 0.1$ kPa, the overall resistance decreases slightly with increasing $Q$ and approaches a minimum value of approximately 0.35°C/W. With significant amounts of NCG present, increasing $P_{NCG}$ directly increases $R_{th}$ for a given $Q$ and shifts the entire curve upwards. This is particularly evident at low $Q$, as increasing $P_{NCG}$ to 34 kPa raises $R_{th}$ by almost 400% over the baseline case. As $Q$ increases, however, the vapor mass fraction gradient between the hot and cold sides also increases and reduces the effect of the NCG. This is evidenced by the steady decline of $R_{th}$ with increasing $Q$ for the different $P_{NCG}$ values considered. With NCG present, the device essentially acts like a thermal switch that responds passively to variations in $Q$. When placed in parallel with a temperature sensitive component of comparable resistance, the switchable $R_{th}$ behavior could be leveraged in combination with a heat spreader or similar to act as a heat flow surge protector. If an active regulation scenario is desired, the amount of NCG could be utilized as the switching mechanism by dynamically modulating $P_{NCG}$ at a given heat flow input. The dynamic scenario opens up a larger range of possibilities for device operation but would require the implementation of a freezing cycle or additional system level components to prevent excess loss of water vapor during multiple chamber
evacuation/pressurization cycles. For the remainder of this paper, we therefore focus primarily on the passive scenario, where $P_{\text{NGC}}$ would be tuned and preset during device fabrication to obtain the desired operating characteristics.

We evaluate the resistance switching in terms of the conventional switching ratio metric, $R_{\text{off}}/R_{\text{on}}$. As the off and on states of our device depend on $Q$, we define $R_{\text{off}}$ and $R_{\text{on}}$ as $R_{\text{off}}$ at the minimum and maximum input powers considered of approximately 0.6 W and 14 W, respectively. With this definition, the maximum switching ratio observed in the experiments is 4 for $P_{\text{NGC}} = 12$ kPa. This is not necessarily the maximum potential switching ratio for the device, however, as the full ranges of $Q$ and $P_{\text{NGC}}$ were not explored. To estimate the maximum potential switching ratio, we examine the limitations for $R_{\text{off}}$ and $R_{\text{on}}$ at low $Q$ is limited by the parasitic conduction resistance $R_{\text{p}}$, which we estimate using a finite element simulation to be approximately 6.7°C/W (the details are given in the supplementary material). As $Q$ increases and $R_{\text{NGC}}$ declines, the minimum value for $R_{\text{on}}$ is measured to be 0.55°C/W from the results for minimal non-condensable gas ($P_{\text{NGC}} < 0.1$ kPa), representing the contribution from the wick and interfacial resistances. Based on these estimates, the maximum switching ratio of the current device must be less than or equal to 12. For future optimization, minimizing the area for sidewall conduction could increase $R_{\text{w}}$ and using a lower resistance wicking structure such as biporous sintered copper could reduce the wick and interfacial resistances within the device.22 Both optimization strategies would have interdependent effects on $R_{\text{on}}$, however, and further experimentation is necessary to identify the overall impact on $R_{\text{off}}$ and $R_{\text{on}}$.

An interesting trend emerges in Fig. 3(a) when $R_{\text{on}}$ is plotted against $\Delta T$ as opposed to $Q$. Except for the baseline case, $R_{\text{on}}$ decreases rapidly at a given critical temperature difference, $\Delta T_c$, which depends on $P_{\text{NGC}}$. Varying $P_{\text{NGC}}$ shifts the critical $\Delta T_c$, where the resistance begins to decline. The values of $\Delta T_c$ for $P_{\text{NGC}} = 12$ kPa, 23 kPa, and 34 kPa are approximately 16°C, 20°C, and 26°C, respectively. Further details are given in Fig. 3(b), where $\Delta T$ is plotted vs $T_{h,\text{avg}}$. In the presence of NCG, $\Delta T$ becomes clamped to a relatively fixed value of $\Delta T_c$, at a certain threshold temperature, $T_{h,c}$, which varies based on $P_{\text{NGC}}$. We define the initiation of clamping as the point when $\Delta T$ is within 1°C of $\Delta T_c$. With these criteria, $T_{h,c}$ equals 61°C, 71°C, and 78°C for $P_{\text{NGC}} = 12$ kPa, 23 kPa, and 34 kPa.

We examine the physics of mass transport in the NCG cavity to elucidate the dependence of $\Delta T_c$ and $T_{h,c}$ on $P_{\text{NGC}}$. We assume that vapor can evaporate and condense freely at the vapor/liquid interfaces above the porous wick, but there is no significant dissolution of NCG into the liquid, and the net mass flux of NCG must therefore equal zero. As a mass fraction gradient in NCG naturally exists due to the complementary vapor mass fraction gradient, however, the zero flux condition for the NCG is preserved through an induced counterdiffusion velocity that counteracts the mass fraction gradient driven motion of the NCG. This creates a net advective and diffusive effect on the vapor transport. The vapor mass flux in this scenario can be described by Maxwell-Stefan diffusion23,24 (further details are given in the supplementary material). The hot side vapor mass fraction, $\omega_h$, is related to the heat input as

$$\omega_h = 1 + (\omega_i - 1) \exp \left( -\frac{Q_z}{p_m D_{cg} h_{lg} A} \right),$$

where $p_m$ is the mixture density, $D_{cg}$ is the binary diffusion coefficient, $h_{lg}$ is the latent heat of vaporization of water, $\omega_i$ is the cold side vapor mass fraction, $A$ is the area normal to the vapor transport, and $z$ is the cavity height. Assuming for the moment that all the heat input goes toward phase change, analyzing the behavior of Eq. (1) reveals that as $\omega_h$ approaches 1, $d\omega_h/dQ$ decays exponentially with increasing $Q$. In terms of temperature, as $T_{h,\text{avg}}$ approaches the saturation temperature of water at the total cavity pressure, $T_{sat}(P_{tot})$, the NCG mass transport resistance decreases such that large increases in heat input lead to
relatively smaller increases in \( \omega_h \) and subsequently \( T_{h,\text{avg}} \). This causes \( dT_{h,\text{avg}}/dQ \) to decline, potentially initiating the clamping behavior for \( \Delta T \). We confirm our theory by estimating \( T_{\text{sat}}(P_{\text{nCG}}) \) for each \( P_{\text{nCG}} \) at the onset of clamping when \( T_{h,\text{avg}} = T_{c,\text{avg}} \) (the details are given in the supplementary material). In each case, the experimentally observed \( T_{h,c} \) is within 8%–12% of the estimation for \( T_{\text{sat}}(P_{\text{nCG}}) \). Note that as \( T_{h,\text{avg}} \) approaches \( T_{\text{sat}}(P_{\text{nCG}}) \), there is also the possibility of the initiation of boiling within the wick. In this case, the hot side wick resistance would potentially decrease and further reduce the total device resistance.

Figure 4 provides more insights into the change in hot side temperature behavior for \( T_{h,\text{avg}} \) greater than \( T_{h,c} \). \( T_{h,\text{avg}} \) and \( T_{c,\text{avg}} \) are plotted as functions of the input power, \( Q \), for \( P_{\text{nCG}} = 34 \) kPa. The dashed lines are provided as visual guides to track the change in the slope for \( T_{h,\text{avg}} \) vs \( Q \). As the experimental cold side is not a fixed reservoir, \( T_{c,\text{avg}} \) shows a linear dependence on \( Q \) due to the constant heat transfer coefficient boundary condition enforced by the cold plate. At location 1 on the plot, \( dT_{h,\text{avg}}/dQ \) is greater than \( dT_{c,\text{avg}}/dQ \) and \( \Delta T \) increases with increasing \( Q \). For \( T_{h,\text{avg}} > T_{h,c} \), however, \( dT_{h,\text{avg}}/dQ \) begins to decline as \( R_{\text{nCG}} \) decreases significantly based on the principles of Maxwell-Stefan diffusion and approaches a value equal to the slope of the cold side temperature. At locations 2 and 3 on the plot, \( dT_{h,\text{avg}}/dQ \) is approximately equal to \( dT_{c,\text{avg}}/dQ \), initiating the clamping behavior for \( \Delta T \).

The \( \Delta T \) clamping behavior of the device is comparable to the characteristics of an electrical varistor, which demonstrates a current-independent clamping voltage beyond a critical transition voltage. Borrowing from the electrical varistor literature,25 we create a power law fit for \( Q \) vs \( \Delta T \) to assess the clamping effectiveness of the device. The relation can be written as

\[
Q \propto \Delta T^\beta,
\]

where \( \beta \) is the nonlinearity coefficient that describes the strength of the \( \Delta T \) clamping, and a higher \( \beta \) represents a stronger clamp. The fit is performed separately for the leakage region of the device and the clamping region where \( \Delta T \) is pulled to \( \Delta T_c \). The fitted curves for \( Q \) vs \( \Delta T \) based on Eq. (2) are plotted against the experimental data for each of the different NCG charge pressures in Fig. 5, with an average root mean square discrepancy between the fits and measurements of \( \pm 1.8 \) W. The average fitted nonlinearity coefficients in the leakage and clamping regions are \( \beta_l = 1.4 \) and \( \beta_c = 8.5 \pm 1 \), respectively. The contrast between the two coefficients delineates the clear change in \( \Delta T \) behavior once clamping is initiated. We note that commercial metal-oxide electrical varistors can achieve clamping coefficients of up to 80.25 A direct comparison of \( \beta_c \) is not necessarily relevant, as the voltage and current operating ranges of electrical systems are often orders of magnitude larger than thermal system analogies (\( \Delta T \) and \( Q \)). However, as power dissipation levels continue to increase in electronic packages, higher clamping coefficients and further device optimization may be desirable.

In conclusion, we have demonstrated a passive thermal device that leverages vapor diffusion through a NCG barrier to exhibit a switchable resistance over a range of power inputs. The resistance decreases by up to 4 times as the input power increases, making the device concept suitable for use in passive surge protector systems against sudden power spikes. The device also demonstrates the ability to clamp the temperature difference across the hot and cold sides to a heat flow independent, fixed value of \( \Delta T_c \). Both the resistance switching behavior and the value of \( \Delta T_c \) are adjustable with the amount of NCG charge, an advantage over many existing regulators that are limited to fixed operating temperature ranges. The tunability of the device presented here provides a valuable addition to the current arsenal of electrothermal circuitry components and increases the opportunity for electrothermal codesign in future systems.

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**FIG. 4.** \( T_{h,\text{avg}} \) and \( T_{c,\text{avg}} \) vs input power, \( Q \), for \( P_{\text{nCG}} = 34 \) kPa. At location 1, \( T_{h,\text{avg}} < T_{h,c} \) and clamping has not initiated, causing \( \Delta T \) to increase with increasing \( Q \). At location 2, \( T_{h,\text{avg}} > T_{h,c} \) and \( dT_{h,\text{avg}}/dQ \) is approximately equal to \( dT_{c,\text{avg}}/dQ \) (location 3), which results in the \( \Delta T \) clamping behavior.

**FIG. 5.** Power fit for \( Q \) vs \( \Delta T \) for \( P_{\text{nCG}} = 12 \) kPa, 23 kPa, and 34 kPa to extract a nonlinearity coefficient, \( \beta \), to describe the strength of the \( \Delta T \) clamping. The average nonlinearity coefficients for the leakage region and clamping region are \( \beta_l = 1.4 \) and \( \beta_c = 8.5 \pm 1 \), respectively.
See the supplementary material for further details on device fabrication, experimental components, and onset of clamping calculations.

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