Supplementary information

Supplementary Note 1: Temperature calculations

Calculation Method

The temperature distribution within the magnetic tunnel junctions is calculated using the COMSOL version 4.2a finite element software package, utilizing the heat transfer module. By solving the heat transfer equation, the laser heating is taken into account as a volumetric heating source $q_V$,

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (\kappa \nabla T) = q_V,$$

where $\rho$, $c$, and $\kappa$ are the material density, the heat capacity, and the thermal conductivity, respectively. The parameters used for the simulations are given in supplementary table 1.

**Supplementary Table 1** Material parameters as given in reference 1, except for $Ta_2O_5$, these parameters are taken from reference 23.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ [kg m$^{-3}$]</th>
<th>$c$ [J mol$^{-1}$ K$^{-1}$]</th>
<th>$\kappa$ [W m$^{-1}$ K$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>19.3</td>
<td>128</td>
<td>320</td>
</tr>
<tr>
<td>Co$<em>{20}$Fe$</em>{60}$B$_{20}$</td>
<td>8.2</td>
<td>440</td>
<td>87</td>
</tr>
<tr>
<td>Ru</td>
<td>12.4</td>
<td>238</td>
<td>117</td>
</tr>
<tr>
<td>MgO</td>
<td>3.6</td>
<td>935</td>
<td>4</td>
</tr>
<tr>
<td>Ta</td>
<td>16.7</td>
<td>140</td>
<td>57</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>8270.0</td>
<td>135.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Calculation Results

The vertical (out-of-plane) temperature gradients between the top and bottom CoFeB electrode for different positions of the laser heating spot are shown in supplementary figures 1-4. Supplementary figures 1-3 show heating scenarios, when the laser spot is located at the MTJs edge, which corresponds to the scenarios used in figure 1c-e in the main article for the in-plane temperature. All three scenarios show, that in the vicinity of the heating laser spot, the temperature difference is around 50 mK showing some fluctuations towards the MTJs edge and decreasing exponentially below 1 mK after 3 $\mu$m away from the heating laser spot. This is depicted in the extraction of the temperature profiles for the vertical (red line) and horizontal (blue line) direction in supplementary figures 1 and 3, and the $45^\circ$ direction (green line) in supplementary figure 2. Note, that the additionally plotted green lines in the vertical and horizontal profile plots in figure 2 are the projections of the $45^\circ$ temperature profile onto those directions.
Supplementary Figure 1 Temperature difference \( \Delta T_{\text{top-bottom}} \) between the two CoFeB electrodes (out-of-plane temperature gradient) when the heating laser spot is located at the edge along the long ellipse axis, as indicated by the red dot in panel a. The horizontal \( \Delta T_{\text{top-bottom}} \) profile (blue line in panel b) shows the average temperature difference along the short ellipse axis for a 1 \( \mu \)m broad strip at center position. The dashed gray area indicates the \( Ta_2O_5 \) surrounding the MTJ area. The vertical \( \Delta T_{\text{top-bottom}} \) profile (red line in panel c) shows the average temperature difference along the long ellipse axis for a 1 \( \mu \)m broad strip at center position. The vertical profile shows temperature difference fluctuations at the MTJs edge around the value of 50 mK decaying exponentially to below 1 mK at the MTJs center around 3 \( \mu \)m away from the heating source.

Supplementary figure 4 shows the scenario, when the heating laser spot is located in the MTJs center. In this case, the maximum temperature difference \( \Delta T_{\text{top-bottom}} = 20 \) mK between both CoFeB electrodes is lower than for the other three scenarios. Simultaneously, \( \Delta T_{\text{top-bottom}} > 10 \) mK for the majority of the MTJs area. This results in higher Seebeck voltages for both magnetization configurations, \( V_p \) and \( V_{ap} \), than compared to a scenario, where the sample is heated at the edge (Compare figure 2a of the main article and supplementary figure 5). This yields Seebeck coefficients \( S_p \approx 600 \mu \text{V} \cdot \text{K}^{-1} \) and \( S_{ap} \approx 1000 \mu \text{V} \cdot \text{K}^{-1} \) for the parallel and antiparallel magnetization configuration respectively. Those values are in the same order of magnitude as earlier findings for this choice of substrate, barrier and electrode material \(^4\).

Because of the central heating, the in-plane temperature gradient is the same for all opposite directions. Therefore, the net \( \Delta T_{\text{in-plane}} = 0 \) and the difference \( V_{p1} - V_{p2} = 0 \), as can be seen in supplementary figure 5 and also in figure 2b in the main article. That means, that possible anomalous Nernst effect contributions cancel each other out, while the TMS effect reaches the highest ratio of \( \text{TMS} \approx 60\% \), similar to the ratios obtained in the experiments published in reference \(^5\).
Supplementary Figure 2 Temperature difference $\Delta T_{\text{top-bottom}}$ between the two CoFeB electrodes (out-of-plane temperature gradient) when the heating laser spot is located at the edge at an $45^\circ$ angle to both principal ellipse axes, as indicated by the red dot in panel a. The horizontal $\Delta T_{\text{top-bottom}}$ profile (blue line in panel b) shows the average temperature difference along the short ellipse axis for a 1$\mu$m broad strip at center position. The dashed grey area indicates the $\text{Ta}_2\text{O}_5$ surrounding the MTJ area. The vertical $\Delta T_{\text{top-bottom}}$ profile (red line in panel c) shows the average temperature difference along the long ellipse axis for a 1$\mu$m broad strip at center position. Both profiles along the principal ellipse axes show a lower starting temperature difference. Additionally, the $45^\circ$ diagonal profile (green line in panel d) shows a starting temperature difference of around 50 mK in the vicinity of the heating source and decaying to below 1 mK after 3$\mu$m.
**Supplementary Figure 3** Temperature difference $\Delta T_{\text{top-bottom}}$ between the two CoFeB electrodes (out-of-plane gradient) when the heating laser spot is located at the edge along the short ellipse axis, as indicated by the red dot in panel a. The horizontal $\Delta T_{\text{top-bottom}}$ profile (blue line in panel b) shows the average temperature difference along the short ellipse axis for a 1$\mu$m broad strip at center position. The dashed grey area indicates the $T\alpha_2O_5$ surrounding the MTJ area. The vertical $\Delta T_{\text{top-bottom}}$ profile (red line in panel c) shows the average temperature difference along the long ellipse axis for a 1$\mu$m broad strip at center position. The horizontal profile shows temperature difference fluctuations at the MTJ edge around the value of 50 mK decaying exponentially to below 1 mK at around 3 $\mu$m away from the heating source.
Supplementary Figure 4  Temperature difference $\Delta T_{\text{top-bottom}}$ between the two CoFeB electrodes (out-of-plane gradient) when the heating laser spot is located at the center of the MTJ (a), as indicated by the red dot. The maximum $\Delta T_{\text{top-bottom}}$ is around 20 mK and decreasing to the edges, as indicated by both, the horizontal (b) and the vertical (c) temperature profile extracted for 1 $\mu$m broad strips. A temperature difference larger than 10 mK is reached for the major part of the MTJs area.

Supplementary Figure 5  TMS measurement curve showing the Seebeck voltage vs. the external field (red line) recorded for the central heating scenario as shown in supplementary figure 4. The ranges with parallel and antiparallel magnetization alignment of both electrodes are indicated by the black arrows. The difference between the voltage measured in parallel magnetization configuration for both directions $V_{p1}$ and $V_{p2}$, $\Delta V_{\text{ANE}} = 0$, because there is no effective in-plane temperature gradient.
Supplementary Note 2: Data Reproducibility

Supplementary Figure 6: ANE measurements for different MgO barrier thickness from 8 to 10 monolayers (ML). The data is extracted from TMS measurements using the same procedure as described in the main manuscript. The MTJ position is outlined by the black line in the false color-coded projection of the ANE signal. The applied magnetic field is oriented in the y-direction for all measurements.

Supplementary figure 6 documents the data reproducibility of the ANE, showing measurements on samples with different MgO barrier thicknesses. The plotted data is extracted from TMS measurement curves using the same procedure as introduced in the main manuscript. For those measurements, the MTJ was oriented with the long axis parallel to the external magnetic field (indicated by the black outline). The external field is oriented along the y-axis for all measurements. The data shows, that there is no significant change in the magnitude or the pattern of the extracted ANE voltage $\Delta V_{\text{ANE}}$. The data extracted around the outline of the MTJ edge shows the same pattern as described by equation 2 and shown in figure 2c in the main manuscript.

Supplementary Note 3: Role of the MgO barrier

We originally searched for the magneto-Seebeck effect in MTJs. The extracted voltage contribution from the ANE is a contribution generated by in-plane temperature gradients and in-plane magnetization which influences the measured Seebeck voltages. That concludes, that an MTJ with an intact MgO barrier is essential for the detection of the ANE in our configuration. The results are displayed in figure 2b in the main manuscript as well as in supplementary figure 6. In addition, supplementary figure 7 shows measurements performed following the same procedure as described in the main manuscript on an MTJ after dielectric breakdown. The breakdown was induced by increasing the voltage above 10 mV until the resistance dropped from the k$\Omega$ range to several $\Omega$. At first, the effect appears larger, as the voltage difference between $V_{p1}$ and $V_{p2}$ is larger, than in measurements with intact tunnel barriers (see supplementary figure 7a). Further, the measurement curve shows clear hysteresis characteristics. However, after performing a 2-dimensional scan and extracting the voltages $V_{p1}$ and $V_{p2}$, see supplementary figure 7b, it shows no centrosymmetric voltage signal, but a high positive peak voltage, when the MTJ is heated on one edge and a low negative constant voltage on the other edge for all in-plane temperature gradient angles with respect to the magnetization direction. There is no sign change for the reversal of the magnetic field, which is expected from the definition of the ANE in equation 2 in the main manuscript. Moreover, the difference $V_{p1} - V_{p2}$ is always positive and has a peak which cannot be accounted for any possible magneto caloritronic effect.
Exemplary Seebeck voltage vs. applied magnetic field measured on an MTJ with a broken MgO barrier is shown in panel a. Panel b shows the Voltages $V_{p1}$ and $V_{p2}$ extracted from measurements introduced in a while moving the laser heating spot. The dashed arrows indicate the heating spot position on the MTJ, at which the voltage was recorded. Panel c shows the difference of the signals $V_{p1}$ and $V_{p2}$. The dashed elliptical outline indicates the size and position of the MTJ.
Supplementary References