Thermal rupture in a Permalloy stripe

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ABSTRACT.

In this work we have tested the thermal rupture of a Permalloy stripe when a current density is flowing through the stripe. For a stripe that has the top surface exposed to air or covered with a thin insulating layer, we find that the stripe gets destroyed at a DC current density of only ~$0.6\cdot10^{12}$ A/m^2 and a mild temperature smaller than 400 K, while it can withstand a current density of ~$1.5\cdot10^{12}$ A/m^2 and a temperature of ~1200 K if the current is delivered in a sub-μs pulse. If the Permalloy stripe is covered with a heat dissipation window of Ta_2O_3/Pt or Ta_2O_3/Au, so the Permalloy can conduct heat also through the top surface, the stripe can hold a current density of ~$3.5\cdot10^{12}$ A/m^2 for a pulsed current, reaching a temperature of ~2000 K underneath the dissipation window. Curiously, the stripes always break in the section not covered by the dissipation window, even if that is not the hottest part of the stripe. Therefore, the layers forming the dissipation window, help with the extraction of heat but they also help by preventing the structural damage in the stripe. Our results suggest that, with the use of a dissipation window and very short current pulses, researchers should be able to perform experiments at current densities close to 10^{13} A/m^2, which would open an opportunity to push the limits of spintronic devices.

Recently, a number of authors, have focused their attention to the problem of Joule heating in nanostripes[1,2,3,4]. A good percentage of the devices used in modern spintronic experiments are based on a nanostripe where an electric current is used to achieve a local change in the magnetization, a domain wall displacement[5,6,7], a magnetic resonance[8], a magnetic switching[9], a domain wall transformation[10], an enhancement of the Exchange Bias[11], assist the nucleation of a skyrmion[12], etc. In these experiments, the electric current delivered to the nanostripe is often large enough to produce a non-negligible Joule heating. This can lead to a misinterpretation of the results[13,14] mainly because, despite the theoretical work available[15,16], predicting the temperature of the nanostripe under Joule heating conditions is a complex problem. A tutorial published recently[17] summarized the key parameters that have to be considered to make a quick calculation of the maximum temperature reached under a given current density. Ref.17 also proposed a fabrication method to maximize the current density that the nanostripe can withstand without irreversible damage. The idea relies on depositing a window on top of the nanostripe with one or several layers that help with the dissipation of heat. In this work we test experimentally some of the concepts proposed in Ref.17. Here we show that the use of a dissipation window deposited on top of a Permalloy stripe, allows a sizable increase of the maximum current density that the stripe can withstand without irreversible damage. The coating layers, additionally to assist with the dissipation of heat, they seem to prevent the magnetic stripe from having thermally induced structural deterioration. When the electric current delivered to the magnetic stripe is DC, the rupture of the magnetic stripe happens at an unexpectedly low current density and temperature. The irreversible damage of the nanostripe might not be linked exclusively to being at a high temperature but also to the time the nanostripe is exposed to that high temperature.

In all the experimental work related to the effect of an electric current on a magnetic micro or nano-stripe, the top surface of the nanostripe is exposed to the air or covered by a very thin insulating layer to avoid oxidation. Therefore, the top surface can only dissipate heat by convection or radiation which, at the nanoscale, is a negligible cooling mechanism[3,1]. Guedas et al. (Ref.17) proposed to coat the top of the magnetic stripe with a window made out of a thermally conductive layer as shown in Fig. 1(a). By doing that, at the negligible cost of having to add one lithography step to the fabrication route, the top surface becomes an additional heat conductive channel. The heat can be diffused trough the top surface of the magnetic stripe to the layers above and then be transported laterally through these top layers until it sinks back to the substrate, as indicated with red arrows in Fig. 1(a).

The measurements in this work are performed over a device fabricated as follows. The Permalloy (Py) stripe, Cr(1 nm)/Py(10 nm)/Pt (2 nm) is deposited over a Si/SiO_2 (25 nm) substrate and contacted with Cr(7 nm)/Au (150 nm) pads with standard lithography techniques. Then, a window of 17 nm thick electrically insulating Ta_2O_3 is deposited on top, covering the Py stripe and the contact pads. Finally, a 5 μm wide and 50 nm thick window of Au, Pt or Ta_2O_3 is deposited on top of the Ta_2O_3 layer as shown in Fig. 1(a). The first 17 nm thick Ta_2O_3 layer prevents from shorting the Py stripe with the top conductive layer. A SEM photograph of one of the devices is shown in Fig. 1(b).

The top layers forming the dissipation window could also be made out of a single electric insulator but good thermal conductor, such as Sapphire. Using a single material as a top layer would save one lithography step but the adhesion to the magnetic stripe has to be good to avoid a large surface thermal resistance at the top surface.

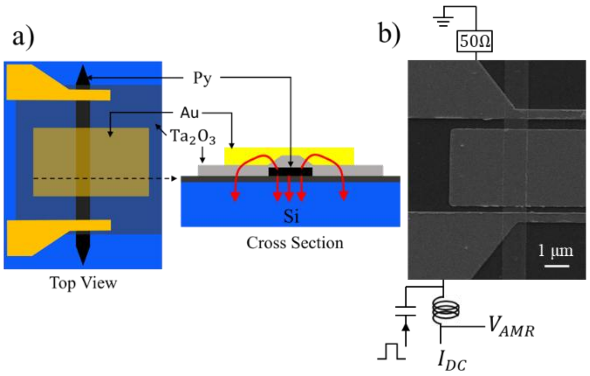

FIG. 1. (a) Cartoon with a top view and a cross section of one of the devices used in this work. (b) SEM image of one the devices and the measuring setup for both the DC and pulsed electric current experiments.

The first measurements were performed using a DC current flowing through the nanostripe. In order to monitor indirectly the temperature of the stripe, we measure the Anisotropic Magnetoresistance (AMR) of the Permalloy, with the set-up shown in Fig. 1(b). As we increase the DC current density delivered to the device, the temperature will increase and AMR will tend to zero as we approach the Curie temperature. For a given DC current density flowing through the stripe, the resistance of the stripe is measured with an external saturating magnetic field applied perpendicular ($R_{\perp}$) and parallel ($R_{\parallel}$) to the stripe axis. The Anisotropic change of resistance is taken as $\Delta R = R_{\parallel} - R_{\perp}$. We do not normalize by $R_{\parallel}$ because the resistance of the Py nanostripe changes slightly by capping it with the layers of the dissipating window. Therefore, the normalization of the AMR would make the comparison between the samples unclear.

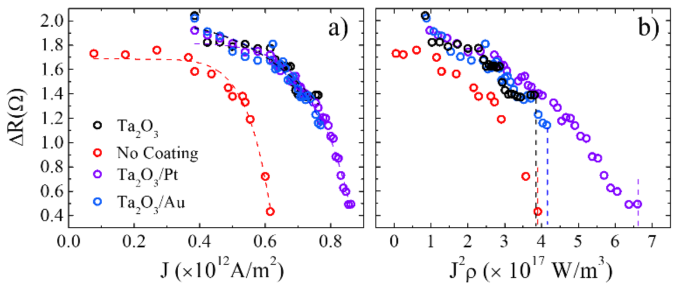

FIG. 2.(a) Anisotropic resistive change $\Delta R = R_{\parallel} - R_{\perp}$versus the DC current density flowing through the Py stripe for the different devices used in the DC experiment. The dotted lines are the fitting of the experimental points to the Bloch law. (b) Same values of ΔR versus the power per unit of volume delivered by the current.

Figure 2(a) shows the results for four different configurations: stripe without dissipation window (red), with a dissipation window of Ta_2O_3 (17nm)/Ta_2O_3 (50 nm) (black), with a dissipation window of Ta_2O_3(17 nm)/Au(50 nm) (blue) and with a dissipation window of Ta_2O_3(17 nm)/Pt(50 nm) (purple). The measurement shown in Fig. 2(a) ends with the maximum current density that allows a reproducible measurement, without destruction or irreversible damage of the stripe. As it can be seen, none of the devices reaches the Curie temperature of the Py ($\Delta R = 0$) before irreversible damage. All the samples with a dissipation window, require a larger current density to achieve a significant decrease of ΔR (or a significant increase of the temperature). This indicates, at least qualitatively, that the coating layers are helping with the dissipation of heat. As the resistance in each of the devices is slightly different and it changes with temperature, an alternative representation of the results is to plot ΔR versus the power per unit of volume delivered by the electric current, $J^2\rho$, as shown in Fig. 2(b). There are only marginal differences between Fig. 2(a) and 2(b), but it is clearer that the Ta_2O_3 device breaks for smaller power per unit of volume than the one with Ta_2O_3/Au. Also, it is noticeable that the device that can withstand more current density and more power per unit of volume is the one with a window of Ta_2O_3/Pt on top of the Py stripe.

As the measurement discussed in Fig. 2 does not provide quantitative information of the temperature, we have performed thermal simulations with COMSOL software. For the simulation we have used the Room Temperature (RT) resistivity of Py as ρ_{Py}= 68·10^{-8} Ω·m, which is the one leading to the experimental resistance of our devices. The RT thermal conductivity of the Py used for the simulation is κ_{Py} = 10.6 W/m·K, which is obtained from the electric resistivity by the Wiedemann–Franz law[18,19]. The rest of the parameters needed for the simulations are taken from the COMSOL libraries. All of them are Temperature dependent. The dimensions are taken from the experimental device, except for the thickness of the Si substrate which is 500 nm in the simulation, although it is 0.5 mm in the experiment. We have previously shown[17] that simulating with a 500 nm thick Si substrate is enough to obtain a precise result of the final temperature in a stripe of the dimensions used in this experiment.

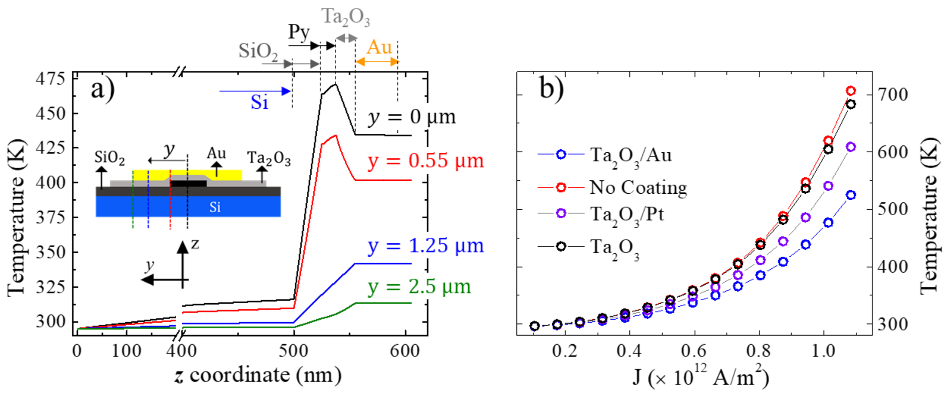

FIG. 3. (a) Temperature profile measured vertically through the different layers (z-coordinate), being z=0 the bottom of the substrate in a sample with a dissipation window Ta_2O_3/Au on top of the Py stripe. The different curves show the vertical temperature profile at different positions along the *y*-axis, as shown in the cartoon: by the middle of the Py stripe(black), at 0.55 µm from the center of the Py stripe (red), at 1.25 µm (blue) and at 2.5 µm (green). (b) Temperature in the middle of the Py stripe versus DC current density for the sample without a dissipation window (red) and for the rest of the samples with different dissipation windows.

First we show that the dissipation window used is wide enough to transport the heat back to the substrate. In Fig. 3(a), we plot the vertical profile of temperatures throughout all the layers under the Py stripe coated with a Ta_2O_3/Au dissipation window. The simulation is done with a DC current density of 10^{12} A/m^2 flowing through the Py stripe. The black curve in Fig. 3a for instance, shows the temperature in the different layers above and underneath the Py stripe. The hottest temperature, ~470 K, is of course in the Py stripe, at a z-coordinate of about 530 nm (being z=0 nm the bottom of the substrate). Above the Py stripe, the temperature drops linearly through the Ta_2O_3 layer (538 nm $< z <$ 555 nm) and plateaus at ~430 K the Au top layer (555 nm $< z <$ 605 nm). Underneath the Py, the temperature also drops linearly through the 25 nm thick SiO_2 layer (500 nm $< z <$ 525 nm) and, by the Si/SiO_2 interface (z = 525 nm), the temperature is 316 K, only few degrees hotter than Room Temperature (295 K). As we move away from the Py stripe along the *y*-axis, the temperature along the *z*-axis gets colder in any of the layers. In particular, the temperature at the Au layer (555 nm $< z <$ 605 nm), drops from ~430 K on top of the Py stripe(*y*=0), to ~340 K at *y*=1.25 µm and to only ~313 K at *y*=2.5 µm. This shows that, the 5 µm wide Au window (2.5 µm on each side of the Py stripe) is enough to conduct all the heat from the top surface of the Py stripe back to the substrate. This is also the case for the other dissipation windows used in this work, Ta_2O_3 and Ta_2O_3/Pt (data not shown).

In Fig. 3b, we show the temperature in the centre of the Py stripe versus the DC current density. This figure shows that the sample reaching the highest temperature for a given current density is the one without a dissipation window, which is what we deduced qualitatively from Figure 2. On the other hand, some details are somehow unexpected. The sample without a dissipation window breaks at 0.6·10^{12} A/m^2 and the simulation predicts a temperature of only 360 K. For the sample with Ta_2O_3, the breakdown DC current density is 0.75·10^{12} A/m^2 and its temperature is 410 K, the sample with Ta_2O_3/Au breaks with 0.75·10^{12} A/m^2 at 371 K and the sample with Ta_2O_3/Pt breaks with 0.9·10^{12} A/m^2 at 446 K. Therefore, the breakdown temperature is quite low in all the cases but also, the breakdown current density does not seem to be related exclusively to temperature.

In Fig. 4 we explore which section of the stripes breaks first. Figure 4a shows a SEM picture of the sample without a dissipation window once broken. We can see that the point of rupture is the middle of the stripe where the simulation predicts 360 K. On the other hand, for the sample with a dissipation window of Ta_2O_3/Pt, Fig. 4(b), the sample breaks just on the edge of the Pt window. If we extract the temperature profile along the length of the Py stripe for the rupture current density in the different samples, Fig. 4(c), we can see that the area adjacent to the top metallic window is the hottest part. Even when the Pt window is very close to the contact pad, as marked by the bottom white arrow in Fig. 4(b), the temperature is ~15 K hotter than in the rest of the stripe. We could conclude that the stripe breaks at the hottest point, but we still we cannot explain why the different samples have a different breakdown temperature if they all break in a region where the cross-section is the same for all of them: there is no Pt or Au, there is only 17 nm of Ta_2O_3 on top of the Py. The results shown so far are repeatable, the samples with Ta_2O_3/Pt are always more resilient and break at a larger DC current density. Therefore, we need additional experiments to draw more solid conclusions.

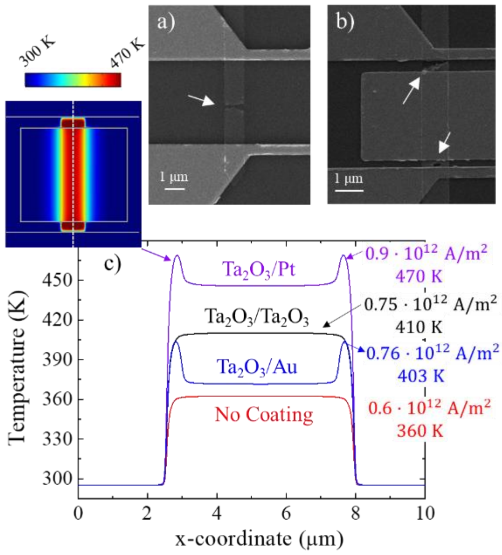

FIG. 4. (a) SEM picture of the zone of rupture in a Py stripe without any dissipation window. (b) SEM picture of the two points of rupture in a Py stripe coated with a dissipation window of Ta_2O_3/Pt. (c) Temperature in the Py stripe along its length for the different samples, following the white dashed line in the cartoon with a colour coded temperature map. Each curve is done at the rupture current density of that particular sample, which labels every curve on the right hand side, together with the maximum temperature of the curve.

In the next set of experiments, we will use a pulsed electric current and a different geometry in the device. Figure 5(a) shows the new geometry where the Py stripe is wider in the section closer to the pads and it narrows to the width of 1μm in the middle section. The dissipation window covers part of the widest section of the stripe, as shown in Fig. 5(d), with the intention of having the hottest point underneath the dissipation window. In this experiment, we deliver a pulse of current through the Py stripe and monitor the shape of the current pulse in a high frequency oscilloscope connected in series at the other end of the stripe. As the amplitude of the pulse increases, at some point, the shape of the pulse gets distorted (the device has been damaged) or we get an open circuit, so the device has been destroyed. By measuring the amplitude of the pulse in the 50 Ω high frequency oscilloscope, we record the value of the rupture current density of the device. In a first experiment, we used an Agilent 81130A pulse generator, which can deliver pulses as short as 1 ns with a maximum amplitude of 4 V over a 50 Ω load. With this pulse generator, we could not damage or destroy any of the devices, even with very long pulses. We then tried with a Standford Research DG535 pulse generator and, using the minimum pulse length of the generator 780 ns, we managed to reach the breaking point of all the devices.

We have performed a simulation with LTspice software to check if any current from the pulse could flow through the top conductive layer (Au or Pt). For this simulation, we assumed the Py and the top conductor (Au or Pt) as parallel resistances. Each layer is discretized in *n* resistive elements with *n-1* nodes. Each of the *n-1* nodes in the Py layer is joined with the corresponding *n-1* node in the Au or Pt top layer with a capacitor corresponding to the Ta_2O_3 layer, using an electric permittivity of this material of $\epsilon_{Ta_2O_3} = 4.577 \cdot 10^{-11}\mathrm{F/m}$. The resistivity for the different layers is the one given by COMSOL except for the Py where we take ρ_{Py}= $68 \cdot 10^{-8}$ Ω·m, which is the value leading to the experimental resistance of our devices. The result of the LTspice simulation (not shown) confirms that none of the current flows through the top conductive layer and all of the current flows through the Py stripe, even for the shortest pulses and the largest amplitudes contemplated in this work.

We begin our discussion on the experiment with pulsed current with the results on a Py stripe without a dissipation window on top. As visible in Fig. 5(b), with a current density of ~1.6·10^{12} A/m^2, the device gets destroyed in the middle section of the stripe. The rupture current density varies from one device to another, although it is always in the range of 1·10^{12} A/m^2. Understandably, different devices are not exactly the same, even if they belong to the same batch and any point defect can trigger the sublimation of the Py stripe. This can make the rupture current density dependent on the precise nanoscopic quality of the stripe. The temperature reached by the Py stripe at that current density is ~1200 K, as shown in the simulation in Fig. 5(c). If we compare the result with the experiment using DC current density, a device without a dissipation window could not reach 400 K before destruction under a DC current (see Fig. 2b), while for a pulsed current, it can reach more than 1000 K. It becomes clear that the rupture of the device is not only due to the temperature it reaches, but also to the time the device is staying at that particular temperature. This may be somehow expected from the point of view of the Boltzmann statistics. If an irreversible damage (sublimation or electron migration of a small volume) happens with a given activation energy E_A, the probability of occurrence of the damage would be proportional to $\exp\{-E_A/k_BT\}$. Therefore, the longer the time the stripe is at a particular temperature, the stronger the chance for the damage to happen.

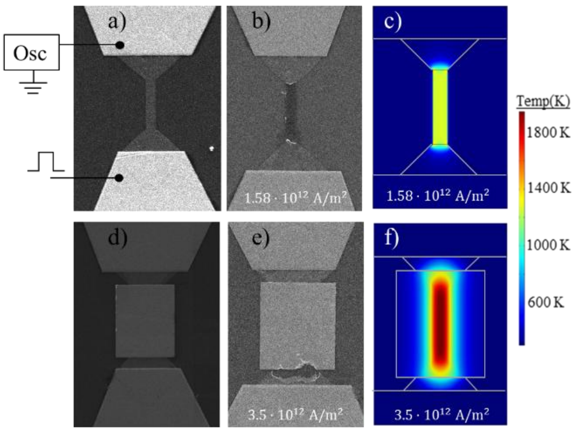

FIG. 5. (a) SEM picture of a device without a dissipation window designed for the experiment with pulsed current with a diagram with the connections to deliver the pulses. (b) Same device blown up after a 780 ns pulse of 1.6·10^{12} A/m^2. (c) COMSOL thermal simulation of the temperature in the device shown in (a) with a pulsed current density of 1.6·10^{12} A/m^2. The rise time of the temperature is only few nanoseconds, therefore, at the end of a 780 ns current pulse, the temperature has reached steady state. (d) SEM picture of a device with a Ta_2O_3/Au dissipation window covering the narrowest section of the stripe. (e) Same device showing that the section of rupture is outside the dissipation window, which is always the case for all the devices tested. (f) COMSOL thermal simulation of the device shown in (d) with a pulsed current density of 3.5·10^{12} A/m^2. Again, the temperature reaches steady state only after few tens of nanoseconds.

Finally, we repeated the pulsed current experiment in a device with a Ta_2O_3/Au dissipation window, which did not show a particularly good performance in the DC experiment. As it can be seen in Fig. 5(e) and Fig. 5(f), with a Ta_2O_3/Au dissipation window on top of the Py stripe, we can reach a much larger current density before rupture, usually in the range of 3.5·10^{12} A/m^2. For this pulsed current density, the Py stripe can reach more than 1800 K in the narrow section underneath the dissipation window. Curiously, none of the devices break at the hottest point underneath the dissipation window, they break on the exposed section although it withstands a smaller current density and a much lower temperature of ~1200 K. This breakpoint temperature ~1200 K is very similar to the one at which the sample without dissipation window breaks (Fig. 5c). In any case, by looking at Fig. 5(e) and 5(f), it is clear that the dissipation window helps to prevent the rupture or irreversible damage of the device. The exact mechanism to explain why this is happening is not clear. Intuitively though, one can assume that when the Py is sandwiched between the substrate and the dissipation window, it would have a bulk-like behaviour as none of its atoms are part of an exposed surface. Therefore, the activation energy for an irreversible local damage (sublimation, electron migration), should be much higher.

If this is the case, an ideal coating material for the dissipation window should be a good thermal conductor but also a material with the right mechanical properties so it is able to partially absorb the energy of the high energy phonons from the Py stripe underneath. The mechanical properties of the Pt may well be behind its good performance as a dissipation window, which always seems to hold the rupture of the Py stripe until higher temperature and current density than the Ta_2O_3/Au dissipation window, despite being the Au much better thermal conductor.

As a conclusion, we have tested experimentally the idea proposed by Guedas *et al.*[17], where one or several layers deposited on top of the magnetic stripe help with the heat dissipation. Using both a DC and a pulsed current density, it is clear that the dissipation window helps with the conduction of heat to the substrate but it also helps preventing the thermal rupture of the stripe. When the current density is delivered in a 780 ns pulse, the Py stripe can hold up to $3.5\cdot10^{12}$ A/m^2 more than twice the current density that the stripe can hold without the dissipation window on top. We also found that the stripe always breaks on a section outside the dissipation window, even if that section is not the hottest part of the stripe. Therefore, the dissipation window not only helps with the dissipation of heat but they it also helps preventing the structural damage of the stripe. Finally, we have found that when the electric current flowing through the Py stripe is DC, the rupture happens at an unexpectedly low current density and temperature. This fact could be somehow expected intuitively but, the simulations show that when the electric current starts to flow through the Py stripe, the rise time of the temperature is less than 100 ns in virtually all cases. Therefore, any pulse larger than few tens of nanoseconds would lead the sample to reach the thermal steady state and it should have the same consequences than applying a DC current. This is not the case as the thermal irreversible damage in the stripe seems to be related to the temperature and the time the stripe is holding that temperature. This can be intuitively understood from the point of view of Boltzmann statistics, as the temperature would increase the probability of irreversible damage but, given enough time, the damage would occur even in the probability is not too high. Our experimental results exceeded our expectations and we believe that, with an optimized coating on top of the Py stripe and using very short current pulses in the range of 1 ns, the stripe should be able to withstand a current density close to 10^{13} A/m^2, opening the window to new experimental ideas.

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AUTHOR DECLARATIONS

Conflict of Interest.

The authors have no conflict of interest to disclose.

Author Contributions.

Rodrigo Guedas fabricated the samples with the assistance of **Manuel Abuín**. The measurements were done mainly by **Alex Novillo** with the assistance of **Rodrigo Guedas**. The simulations were done by **Rodrigo Guedas** with the assistance of **Victor Raposo**, who also did the LTspice simulation. **José L. Prieto** envisioned the experiment, directed the research and wrote the manuscript.

DATA AVAILABILITY STATEMENTS

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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