Impact of The Structure on The Thermal Burnout Effect Induced by Microwave Pulses of PIN Limiter Diodes

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Impact of the structure on the thermal burnout effect induced by microwave pulses of PIN limiter diodes

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Abstract

Positive-intrinsic-negative (PIN) limiter are widely used to protect sensitive components from leakage power itself and adjacent high-power injection. Being the core of a PIN limiter, the PIN diode is possible to be burnt out by the external microwave pulses. Here, numerical simulations by our self-designed device-circuit joint simulator were carried out to study the influences of the I layer thickness and the anode diameter of the PIN diode on the maximum temperature variation curve of the PIN diode limiter. The damage threshold criterion in the numerical simulation was first studied by comparing experimental results with simulation results. Then, we determined the impact of the structure on the thermal burnout effect induced by microwave pulses of PIN limiter diodes.

1. Introduction

In the front-end of a radar system, Positive-intrinsic-negative (PIN) limiter is one of the most important modules to protect the back sensitive devices from leakage power itself and adjacent high-power injection[1-3]. However, with the development of the pulse power technology, the widespread use of radar and the emergence of high-power microwave (HPM) weapons, the electromagnetic environment faced by radar systems is becoming more and more complicated. External microwave pulses can couple into the electronic systems through the antenna and further damage the PIN limiter[3-5].

Being the core of a PIN limiter, the PIN diode is a sensitive semiconductor device, which is possible to be burnt out by the injected HPM pulses. The burnout of the PIN diode may lead to the failure of the radio frequency front end or even the entire electronics system[6, 7]. Thus, many studies have been carried out for damage effects of the microwave pulse for the PIN limiter. Junction burnout, metallization burnout and thermal second breakdown are indicated to be the main cause of the burnout effect by microwave pulses of the PIN diodes[8-11]. However, few literatures about the impact of the structure, especially the I layer thickness and the anode diameter of the PIN diode, on the thermal burnout effect induced by microwave pulses have been reported.

In this work, numerical simulations by our self-designed device-circuit joint simulator were carried out to study the influences of the I layer thickness and the anode diameter of the PIN diode on the maximum temperature variation curve of the PIN limiter. The damage threshold criterion in the numerical simulation was first studied by comparing experimental results with simulation results. Then, we determined the impact of the structure on the thermal burnout effect induced by microwave pulses of PIN limiter diodes.

2. Structure of the studied PIN limiter

A typical PIN limiter includes single or multistage PIN diodes. To eliminate the interferences from other factors except the I layer thickness and the anode diameter of the PIN diode, such as other PIN diodes and complex peripheral circuits, a single-stage limiter, whose structure is shown in Fig. 1, is chosen as the target of the study. The typical single PIN diode limiter consists of one PIN diode, two Direct Current (DC) block capacitors, and a parallel inductor. The inductance of the parallel inductor is 40 nH, the DC block capacitors are all 30 pF in this work and the PIN diodes are model CLA series manufactured by Skyworks[12]. The structure of model CLA series PIN diodes whose material is silicon is shown in Fig. 2. The PIN diode mainly consists of a thick substrate and three layers named P^+, I and N^+ mounted on it.

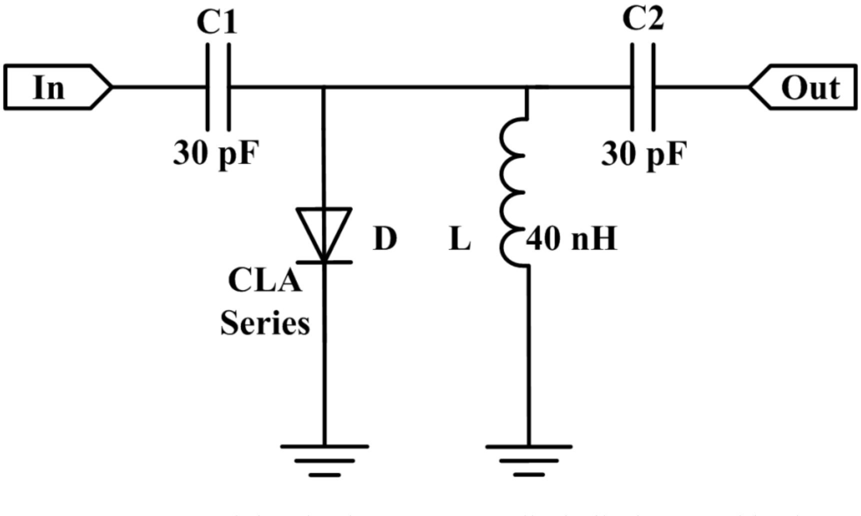

Figure 1. Structure of the single-stage PIN diode limiter used in the study.

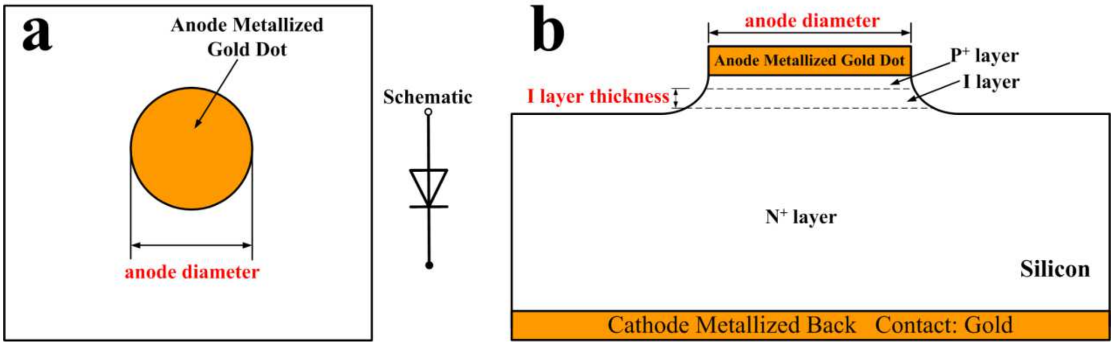

Figure 2. Structure of the model CLA series PIN diode. (a) Top view (b) Side view.

3. Outline of numerical method and validation

In our numerical methodology, a set of semiconductor equations based on the drift-diffusion model[13] are at first solved so as to obtain the transient heat source distribution over the PIN diode, The drift-diffusion model includes the following equations.

Poisson equation

$$\nabla \cdot \varepsilon_m \nabla \varphi = -q\left(p - n + N_D - N_A\right) - \rho_s \tag{1}$$

Where:

ε_m is the permittivity of the silicon.

φ is the electrostatic potential.

q is the elementary electronic charge.

n and p are the electron and hole density, respectively.

N_D and N_A are the density of donors and acceptors, respectively.

ρ_s is the fixed charge or interface state charge in the insulating layer.

Continuity equation

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J_n} - \left(U_n - G_n\right) \tag{2}$$

$$\frac{\partial p}{\partial t}=\frac{-1}{q}\nabla\cdot\mathbf{J_p}-\left(U_p-G_p\right) \tag{3}$$

Where $\mathbf{J_n}$ 和 $\mathbf{J_p}$ are the current densities of electrons and holes, respectively. G and U are the electron-hole generation and recombination rates, respectively.

Carrier transport equation

$$\mathbf{J_n}=qn\mu_n\mathbf{E_n}+k_b\mu_n\left(T\nabla n+n\nabla T\right) \tag{4}$$

$$\mathbf{J_p}=qn\mu_p\mathbf{E_p}-k_b\mu_p\left(T\nabla p+p\nabla T\right) \tag{5}$$

Where μ_n and μ_p are the mobility of electrons and holes, respectively. E represents the intensity of electric field. T is the temperature (K). k_b is the boltzmann constant。

When microwave pulses are applied to the PIN diode, the time dependent heat conduction equation[14] will be further solved to get its transient temperature distribution.

$$\rho c\frac{\partial T}{\partial t}-\nabla\cdot\left[\nabla\left(\kappa T\right)\right]=H\left(t\right) \tag{6}$$

Where ρ is the density (kg/m^3), c is the specific heat (J/kg-K), κ is the thermal conductivity (W/m-K), and H is the heat generation term (W/m^3).

The heat generation in the semiconductor is written as

$$H=H_n+H_p+H_U \tag{7}$$

Where H_n and H_p are lattice heating due to electron transport and hole transport, respectively. H_U is lattice heating caused by carrier recombination and generation.

According to the microstrip circuit of the limiter shown in Fig. 1, the simulation circuit of the PIN limiter is established in the simulator as shown in Fig. 3, where S is the microwave pulse source, the internal resistance of the pulse source R1 is 50 Ω, and L1 and L2 are the equivalent inductance of the PIN diode welding gold wires, and

R2 is the load impedance.

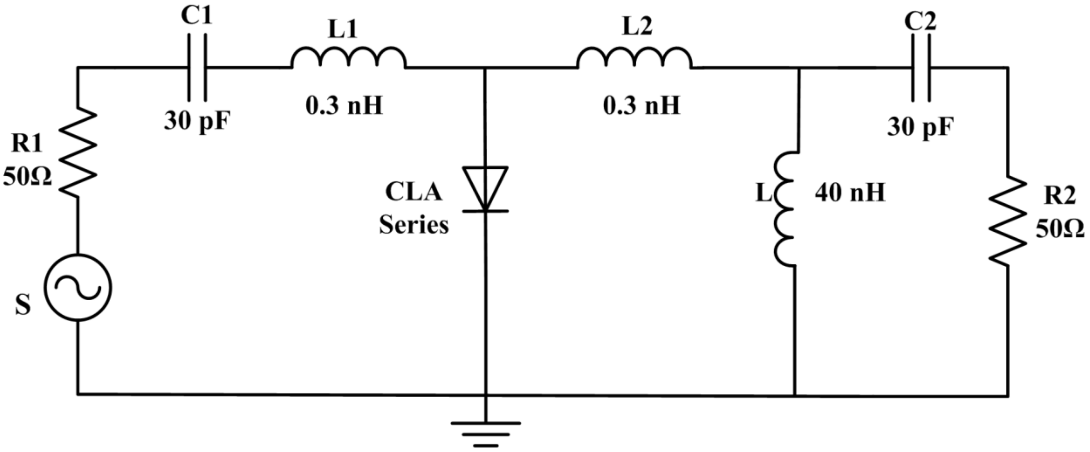

Figure 3. Circuit of PIN limiter for simulation.

The signal caused by the external electromagnetic pulses coupling into the ribbon cable is similar to be a low-damping sinusoidal voltage signal, which can be approximately expressed as

$$U = U_0(sin\, 2\pi f + \varphi) \tag{8}$$

Where U_0 is the amplitude of electromagnetic pulses, f is the pulse frequency, and φ is the initial phase. This simulation does not consider the influence of the initial phase, so the initial phase is set to 0, the pulse frequency is set to 3GHz, and the pulse width is set to 100ns, which are consistent with the experimental settings.

3. Numerical results and discussion

The Skyworks CLA series of silicon limiter diodes have two structures， mesa-constructed and planar-constructed. In this study, the widely used mesa structure devices CLA4601, CLA4602, CLA4604 and CLA4605 were selected for effect experiment research. And compared with the simulation results, the device parameters are shown in Table 1.

	CLA4601	CLA4602	CLA4604	CLA4605
H_i (μm)	1	1	2	2
L_p (μm)	27	29	42	51

Table 1. Structural parameters of the CLA4601,CLA4602, CLA4604 and CLA4605 silicon limiter diodes.

In the numerical simulation of the electromagnetic effect of microwave devices, the maximum temperature criterion in a semiconductor device as the melting point of the specific semiconductor material or electrodes is usually used to determine a burnout phenomenon in the simulation.[11, 16-19] Therefore, the burnout power thresholds of the PIN limiters are at first simulated based on the peak temperature inside the device reaching the melting point of the material (silicon=1688K), as shown in Fig. 4 by red cube.

It is noteworthy that the use of a microwave power limiter generally leads to additional insertion loss in a receiver, which increases its noise figure and reduces its dynamic range.[16] This insertion loss is an important indicator of the microwave power limiters and can be used to evaluate the degree of damage to PIN limiters. In the effect experiment, the limiter insertion loss change of 3dB was used as the damage criterion, and the conventional HPM pulse parameters (the repetition frequency is 20Hz, the action time is 5s) were selected for the experiments. The device damage threshold results obtained by the experiment were shown in Fig. 4 by black ball.

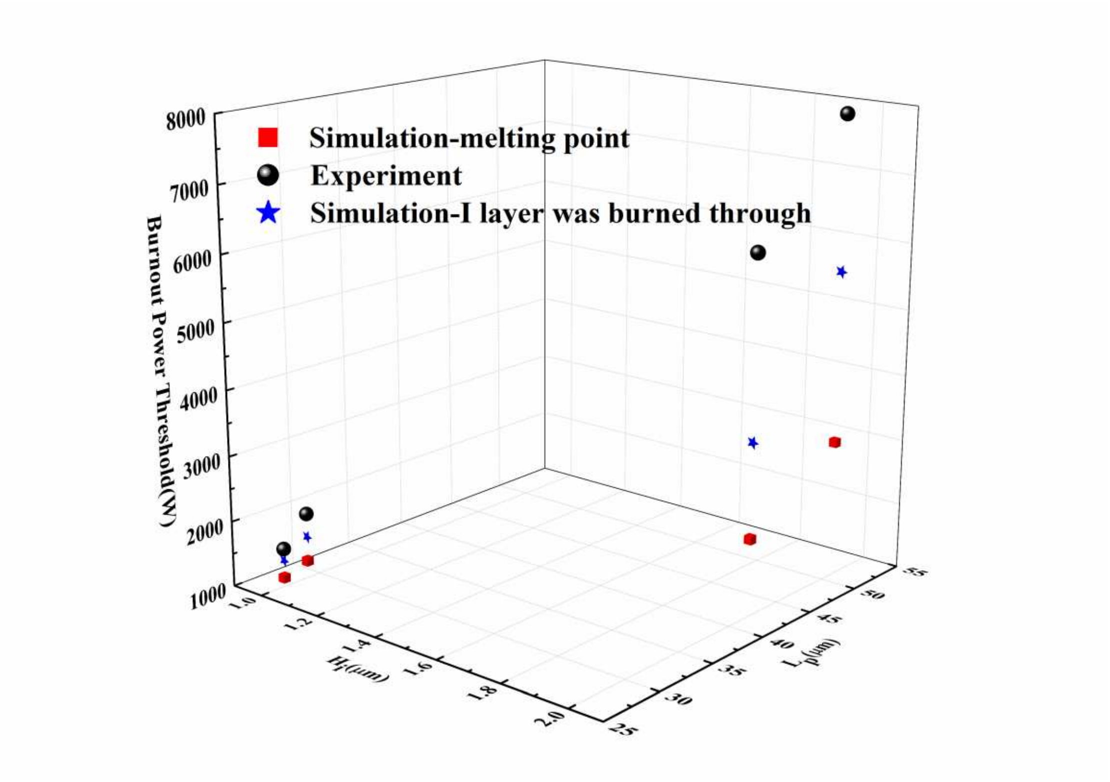

Figure 4. Simulation and experimental results for the CLA4601,CLA4602, CLA4604 and CLA4605 silicon limiters.

It can be seen from Fig. 4 that the experimental results and the simulation results basically have the same trend. The burnout power thresholds increase with the increase of the limiter diodes serial number. However, the experimental thresholds are obviously larger than the simulation results, and the bigger the thickness of the I layer, the more obvious the difference. When the thickness of the I layer is 1μm, the experimental result is close to the simulation threshold, and the difference is within 2dB. When the thickness of the I layer is 2μm, the experimental result is far from the simulation threshold, and the difference is about 4dB. The difference between the burnout power thresholds obtained by simulation and experiment are so huge that it cannot meet the practical application.

The above phenomenon may be caused by the inconsistent damage criteria， Preliminary research results[20] show that it is not accurate to set the maximum temperature criterion in a semiconductor device as the melting point of the specific semiconductor material or electrodes to determine a burnout phenomenon in the simulation. Previous experiments[20] found that the I layer of the limiter has been basically burned through in the longitudinal direction when the insertion loss changed by 3dB. Thus, using the hot spot reaching the melting point of the silicon penetrates the I layer as the damage criterion, the burnout power threshold of the limiters were re-simulated. The simulation results were shown by blue star in Fig. 4. It can be seen that using this device damage criterion, the simulation results are closer to the experimental results. When the thickness of the I layer is 1μm, the difference between the experimental result and the simulation threshold is within 1dB, and when the thickness of the I layer is 2 μm, the difference between the experimental result and the simulation threshold is about 2 dB. This damage criterion is obviously more reasonable and accurate, and both the trend and the threshold are more consistent with the experimental results.

In order to study the influence of the I layer thickness on the HPM burnout power threshold of the PIN limiter, the other parameters are the same as those of the CLA4601 PIN diode except for the thickness of the I layer. The damage thresholds of the devices based on the two damage criteria are simulated respectively, and the simulation results of the relationship between the I layer thickness and the burnout power thresholds are shown in Fig. 5.

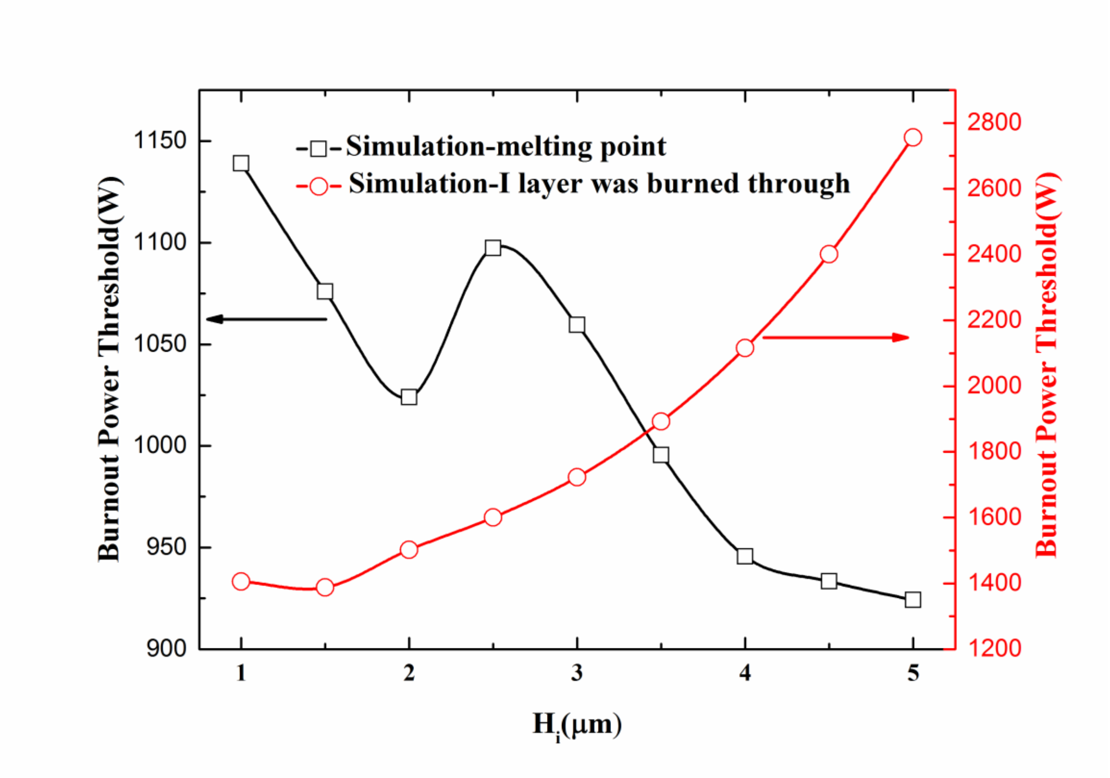

Figure 5. Simulation results of the relationship between the I layer thickness and the burnout power threshold.

The simulation results based on the maximum temperature of the device reaching the melting point of the material are shown in Fig. 5 by black square. The burnout power threshold generally decreases as the thickness of the I layer increases. The reason for this phenomenon may be that as the thickness of the I layer increases, the series resistance of the PIN diode increases, and the voltage coupled to the PIN diode die increases accordingly. At the same time, as the thickness of the I layer increases, the charge storage capacity in the I layer increases. So the peak leakage time is longer, that is to say, it need take longer time to extract the carriers in the I layer to reach the low-resistance limiting state. Therefore, it is more conducive for the PIN diode to absorb more energy to reach the burned state. Also, it should be noted that the burnout power threshold based on the melting point does not change significantly as the thickness of the I layer increases. For example, the difference of the burnout power threshold is just only 0.9dB between the thickness of the I layer is 1 μm and 5 μm.

The simulation results based on the the I layer was burned through are shown in Fig. 5 by red circle. The burnout power threshold basically increase with the increase of the thickness of the I layer, which is consistent with the usual conclusion. The increase of the I layer thickness will enlarge the thermal power capacity of the PIN diode, so more energy is required to burn the I layer.

Apart from the thickness of the I layer, the anode diameter is also one of the important device parameters of the PIN diode. Although the anode diameter of a specific PIN diode has been determined at the factory, it is also meaningful to study and understand the influence of the anode diameter on the burnout power threshold. In order to study the influence of the anode diameter on the HPM burnout power threshold of the PIN limiter, the other parameters are the same as those of the CLA4601 PIN diode except for the anode diameter. The damage thresholds of the devices based on the two damage criteria are simulated respectively, and the simulation results of the relationship between the anode diameter and the burnout power thresholds are shown in Fig. 6.

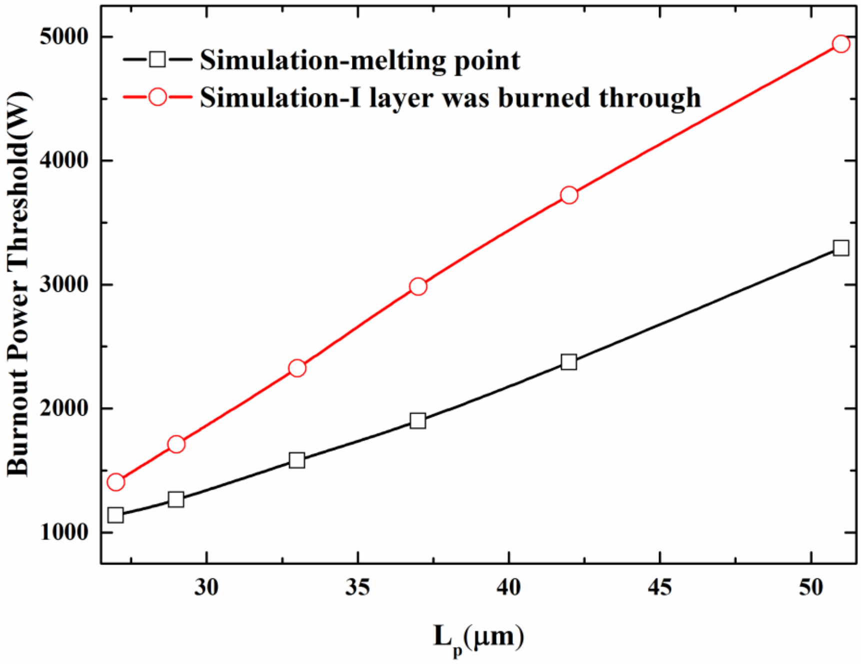

Figure 6. Simulation results of the relationship between the anode diameter of the PIN diode and the burnout power threshold.

It can be seen from Fig. 6 that the anode diameter has a more obvious effect on the burnout power threshold for the burnout of HPM pulse injection. The relationship between the anode diameter of the PIN diode and the burnout power threshold is approximately linear. The main reason for this phenomenon is that the PIN diode with a larger anode diameter has a larger dynamic area (that is, the lateral area of the three layers of P, I and N), which cause the current and thermal power capacity of the device is higher. From the perspective of power density, the larger anode diameter leads to a larger area of the heating disc, and actual received microwave pulse power per unit area is correspondingly lower, resulting in a higher device burnout power threshold.

4. Conclusion

In summary, we investigated impact of the structure on the thermal burnout effect induced by microwave pulses of PIN limiter diodes. We found that using the hot spot reaching the melting point of the silicon penetrates the I layer as the damage criterion to simulate is significantly better than the traditional melting point criterion, and both the trend and the threshold are more consistent with the experimental results. The burnout power threshold basically increase with the increase of the thickness of the I layer and the anode diameter of the PIN diode.

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Author contributions

J.T.Z., G.Z. and C.Y.C. designed the experiments. J.T.Z. and Z.D.C. performed the experiments. J.T.Z. and Q.Y.C. analyzed the data and wrote the main manuscript. All authors reviewed the manuscript.

competing interests

The authors declare no competing interests.