

Ion track formation via electric-field-enhanced energy deposition

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High-energy ion irradiation deposits extreme energy in a narrow range ($\sim 1\text{--}10$ nm) along ion trajectories in solid through electronic energy loss, producing unique irradiation effects such as ion tracks. However, intrinsic velocity effects impose an upper limit on electronic energy loss that cannot be overcome by adjusting irradiation parameters. We introduce a method using electric fields during irradiation to enhance nanoscale energy deposition by accelerating ion-excited electrons within subpicosecond timescales. Our extended field-enhanced thermal spike model quantitatively describes this enhancement and predicts a significant reduction in the electronic energy loss required for ion track formation in amorphous SiO_2 , which is in excellent agreement with experimental observations. This work provides an approach to control energy deposition during irradiation and boosts the wide application of ion tracks in material modification and nanoengineering to much broader extents.

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I. INTRODUCTION

When an energetic ion penetrates a solid, its kinetic energy loss will transfer to the electronic system through inelastic interactions (electronic stopping, S_e) and to the atomic system via elastic collisions (nuclear stopping, S_n). For high-energy irradiation, energy deposition in the target solid is dominated by S_e , while S_n is negligible [1,2]. This energy deposition induces rapid local heating in the solid on tens of nanometer spatial scales and subpicosecond timescales via electro-phonon coupling, followed by heat dissipation over tens to hundreds of picoseconds, forming a thermal spike that brings about various irradiation effects, such as plastic deformation [3], ionization-induced defect annealing [4,5], or even narrow trails of permanent damage along the ion path [6], called “ion track” [2,7]. These unique effects have been extensively used to characterize and modify materials, leading to broad applications in microelectronics [8], geological dating [9], biotechnology [10], and nanomaterial engineering [11–13].

Controlling the confined nanoscale energy deposition E_c in solids is the basis of generating and applying these effects [14]. Generally, E_c equals S_e and can be modulated by varying the incident ion type and energy when using an accelerator for high-energy ion irradiation. However, due to intrinsic velocity effects [15], S_e values exhibit upper limits that cannot

be exceeded by merely adjusting ion parameters. This imposes significant constraints on irradiation applications. For example, ion track formation remains challenging in diamond [16] and crystalline silicon [17], or even impossible in certain materials like silicon carbide [18]. Therefore, in addition to modifying ion parameters, developing an alternative method to enhance the confined energy deposition is essential.

In this study, we introduce a method using external electric fields during irradiation to enhance E_c , which enables ion-excited electrons to gain additional energy within subpicoseconds. Experimental results in this work demonstrate that the applied electric field during irradiation can markedly enhance nanoscale energy deposition, thereby promoting ion track formation in amorphous SiO_2 (a- SiO_2) even under low S_e irradiation. Meanwhile, we extended the thermal spike model and employed multiphysics finite element simulations to describe the field-enhanced E_c (comprising both ion-induced electronic energy loss and the field-accelerated electron energy) and subsequent thermal spike effect. The simulations indicate that field-induced electron energy synergistically evolves with electronic energy loss during sub-picosecond electron-phonon coupling, intensifying thermal spike effects and raising the temperature above the ion track formation threshold, in good agreement with our experiments. This method may open up previously unexplored research areas for irradiation effects and enable innovative applications, including ion-track-based nanopatterning [19,20], defect engineering [21,22], and targeted material modification at the nanoscale [23,24].

II. EXPERIMENT AND RESULTS

A. Experimental setup

We first demonstrate through a carefully designed ion track formation experiment in a- SiO_2 that energy deposition is

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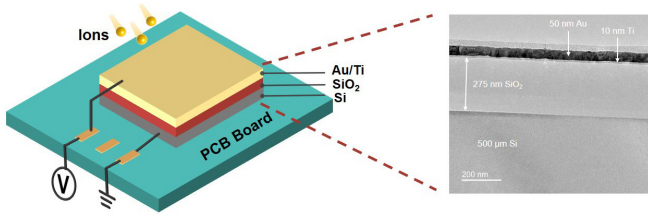


FIG. 1. Schematic of the irradiation test samples. An electron-beam-evaporated Au/Ti top layer and a heavily doped Si substrate serve as electrodes.

substantially enhanced when an electric field is applied during ion irradiation. As a key material for ion-track-based nanofabrication, a-SiO₂ has been used as a model system for elucidating the mechanism of ion track formation over the past decades [2,25].

Ion track formation in solids evolves with increasing nanoscale energy deposition from no track to discontinuous tracks and continuous tracks, leading to distinct morphologies during characterization (e.g., scanning electron microscopy (SEM) after etching) [26–28]. Therefore, we use a comparison of ion track formation with and without an applied electric field as the criterion for field-enhanced nanoscale energy deposition.

In our experiments, 280-nm-thick a-SiO₂ thin films thermally grown on Si substrates are used as samples. These samples are divided into two experimental groups: one subjected to conventional irradiation alone, and another to our electric field enhancement method. We deposited an electron-beam-evaporated Au/Ti layer on the sample surface to serve as an electrode as shown in Fig. 1, and all irradiated samples were equipped with this Au/Ti layer, including the control group.

The two groups of samples were irradiated at 2×1.7 and 2×6 MV tandem accelerators at Peking University, with 2.6 MeV C ions, 4.1 MeV F ions, 6 MeV Si ions, and 20 MeV Si ions at room temperature in a vacuum. Ion impact densities were 2×10^9 to 1×10^{10} ions/cm², and the angles of incidence were set to be 0° with respect to the surface normal. What's different is that the first group was directly irradiated without bias, while the second was irradiated under a uniform electric field—supplied by a dc voltage and aligned with the ion incidence direction—as schematically shown in Fig. 1. Under these irradiation conditions, S_e remains below the *continuous* track threshold in a-SiO₂ ($S_e < S_e^{\text{th}} = E_c^{\text{th}} = 4$ keV/nm [28,29]; Table I), theoretically unable to form continuous ion tracks and likely limited to discontinuous damage features. In

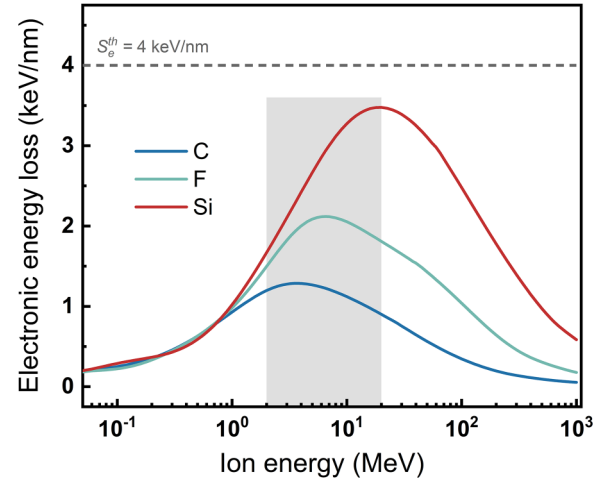


FIG. 2. Electronic energy loss as a function of ion energy for three types of ions (C, F, Si) incident on a-SiO₂, calculated by SRIM-2013 package [30]. The shaded area indicates the ion energy range used in this irradiation experiment. The dashed line represents the energy deposition threshold required for ion track formation in a-SiO₂.

fact, due to the velocity effect, the maximum S_e values for C, F, and Si ion irradiation all remain below S_e^{th} regardless of the incident energy adjustments, as shown in Fig. 2. This suggests that, under conventional irradiation conditions, these ions are unlikely to generate continuous ion tracks in a-SiO₂ and at most may produce discontinuous damage features. Notably, as long as ion track formation is significantly enhanced in the second group compared to the first group, we can conclusively establish that external electric fields significantly enhance energy deposition.

Since ion tracks in a-SiO₂ are “latent tracks” difficult to observe directly, we employed wet etching to assess their formation. In principle, tracks become discernible when the local etch rate along the track (v_t) exceeds the bulk etch rate (v_b). Accordingly, samples with ion track formation exhibit conspicuous surface-etched pits after etching [26–28]. In our experiments, the irradiated samples were mechanically stripped of the surface Au/Ti layer using lift-off tape, followed by ultrasonic cleaning in ethanol and deionized water. Then the irradiated samples were etched in a 4% hydrofluoric acid aqueous solution at room temperature for 5 min [28] to reveal tracks, then rinsed with deionized water, dried with nitrogen, and characterized by SEM [31].

B. Experimental results

Figure 3 compares the SEM surface morphologies of a-SiO₂ under conventional (field-free) irradiation conditions and electric-field-enhanced conditions. Figures 3(a), 3(c), 3(e), and 3(g) display the etched surfaces irradiated with the conventional method; no obvious etched pits of ion tracks (typically appearing as round black spots in the images) can be observed on the a-SiO₂ surfaces. This aligns with general expectations: Under these conditions, most tracks do not form to be etched or are difficult to clearly discern. However, as shown in Figs. 3(b), 3(d), 3(f), and 3(h), etched pits of ion

TABLE I. Ion irradiation parameters. The S_e and S_n are calculated by SRIM-2013 package [30].

Ion	E (MeV)	S_e (keV/nm)	S_n (keV/nm)
C	2.6	1.26	0.004
F	4.1	2.01	0.009
Si	6.0	2.85	0.020
Si	20	3.48	0.007

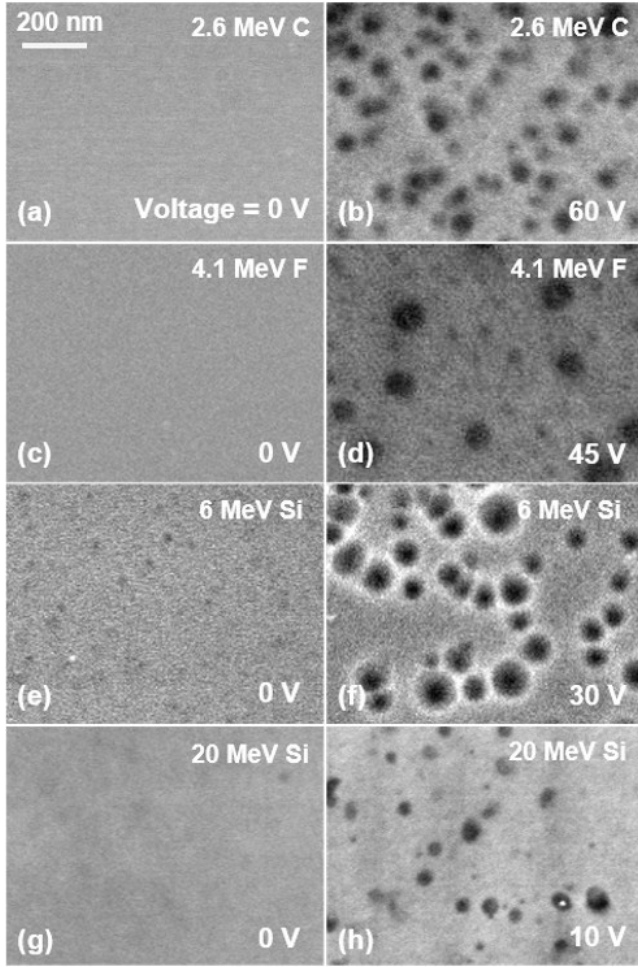


FIG. 3. SEM images of a-SiO₂ films under no electric field and applied field irradiated by (a), (b) 2.6 MeV C ions, (c), (d) 4.1 MeV F ions, (e), (f) 6 MeV Si ions, and (g), (h) 20 MeV Si ions with 2×10^9 to 1×10^{10} ions/cm². The voltage applied during the irradiation is given in each image, and the electric field strength E equals the ratio of voltage to thickness 280 nm, $E = \text{voltage}/280 \text{ nm}$.

tracks become clearly visible when a strong enough electric field is applied, in sharp contrast to the field-free case. This provides direct experimental evidence of the enhancement effect of the applied electric field on the ion track formation. Further SEM results are available in Fig. 4.

Notably, due to differences in irradiating ion species, sample preparation, and etching conditions, the reported S_e threshold for etchable tracks in a-SiO₂ varies across the literature, spanning approximately 1.5–4 keV/nm [28,29]. For the samples irradiated with 20 MeV Si ($S_e = 3.48 \text{ keV/nm}$) in this work, most ion impacts did not result in etchable tracks, fully consistent with the experimental observations reported in Ref. [29].

Accordingly, we adopt the widely accepted threshold for continuous track formation ($S_e^{\text{th}} = 4 \text{ keV/nm}$) as our working criterion, which also renders the with/without-field comparison clearer and more transparent.

Figure 4 presents the ion track formation for four irradiation conditions with different S_e under various applied electric fields. As S_e decreases, a larger field-induced energy

deposition is required to form ion tracks, and thus stronger external fields are needed—a physically natural outcome.

Figure 5 displays the ion track formation conditions using the electric field enhancement method (purple shaded area), which is located in the low- S_e irradiation region below the ion track formation threshold S_e^{th} of a-SiO₂ (shown by the vertical dashed line in the middle); also included is the high- S_e irradiation region (orange shaded area) using the conventional irradiation method. It shows that under irradiation conditions below the conventional S_e^{th} , the present method is still able to successfully form ion tracks, and the required external electric field is roughly a diagonal line in the left part, which is just the threshold energy E_c^{th} . Ion tracks cannot form in the low- E_c irradiation region (white area in the bottom left). These results confirm that applying an external electric field during irradiation significantly enhances nanoscale energy deposition and effectively promotes ion track formation even at low S_e .

III. METHOD AND SIMULATION

A. Field-enhanced thermal spike model

We now discuss the underlying physical mechanisms responsible for electric-field-enhanced ion track formation. The thermal spike model is widely regarded as well describing the nanoscale energy deposition and ion track formation in insulators [32–35]. These models propose that local electrons initially acquire energy from incident ions, followed by energy transfer to lattice atoms through electron-phonon coupling within an extremely short time frame ($< 1 \text{ ps}$) [23], generating localized high-temperature thermal spikes. When the lattice temperature near the ion trajectory rises above the target material's melting point, a melting-phase transition occurs along the trajectory, producing a continuous, heavily damaged zone and thereby giving rise to ion track formation.

In conventional thermal spike models (e.g., the analytic thermal spike model, ATSM [34]), the heat transported through electron-phonon coupling arises exclusively from the electronic energy loss, with no additional sources considered. According to the ATSM, the temperature distribution within the target materials resulting from the swift heavy ions exhibits a Gaussian profile [34,36], which can be written as

$$T(r, 0) = \frac{Q}{\pi a(0)^2 \rho c} e^{-\frac{r^2}{a(0)^2}}.$$

Here, r represents the radial distance from ion path, $a(0)$ is the standard deviation of the Gaussian distribution, ρ is the density, and c is the heat capacity of the target material. Q is the energy absorbed by the localized lattice system per unit depth of target from the electronic system. In the conventional thermal spike model, Q was entirely originating from S_e caused by irradiation, written as $Q = g S_e$, where g is the electron-phonon coupling parameter, indicating the fraction of electronic energy loss contributing to heating. This formula clearly reveals the relationship between temperature and S_e . Because ion track formation requires the temperature to reach the target materials melting point, it also explains why a threshold S_e^{th} must be attained in specific materials.

However, in this work, the energy deposition has gained an additional source from external electric fields, and the

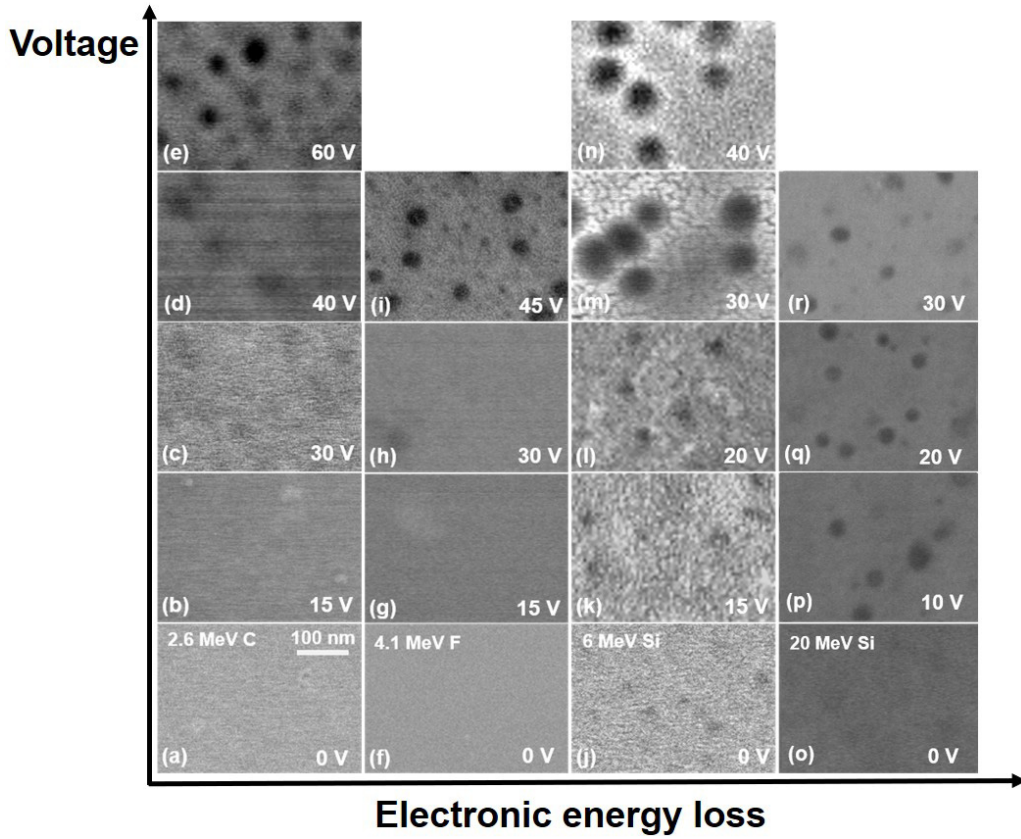


FIG. 4. SEM images of a-SiO₂ films subjected to different voltage irradiated by (a)–(e) 2.6 MeV C ions, (f)–(i) 4.1 MeV F ions, (j)–(n) 6 MeV Si, and (o)–(r) 20 MeV Si. The voltage applied across both film surfaces is given in each image.

subsequent thermal evolution process has also changed, requiring us to extend the field-enhanced thermal spike model.

Figure 6 illustrates our extended field-enhanced thermal spike model incorporating electric field-irradiation synergistic effects. Upon initial ion incidence, electronic energy

deposition induces localized electronic excitation within 10 fs [23], generating abundant electrons. The number of these electrons per unit depth can be quantified as

$$n = \frac{S_e}{\omega} = \frac{S_e}{2.73E_g + 0.55(\text{eV})}$$

[37], where E_g represents the bandgap energy of 8.9 eV, characteristic of a-SiO₂ [38].

In the presence of an external electric field, the excited electrons are directionally accelerated parallel to the field, giving rise to a transient current density J , which is determined by the combined effects of the applied electric field E and electron concentration n . The ensuing charge-transport dynamics are governed by the following electrical equations:

$$\nabla \cdot (\epsilon \nabla V) = -\rho_c,$$

$$\frac{\partial n}{\partial t} + \frac{1}{q} \nabla \cdot J = 0,$$

$$J = q\mu_n n(-\nabla V) + qD_n \nabla n.$$

In this way, electrons can acquire additional energy from the electric field beyond that provided by electronic energy loss. Under a strong field, the drift current formed by electrons parallel to the field is confined around the ion track. These excited electrons thereby gain significant field-induced kinetic energy, intensifying electron-lattice collisions and amplifying the thermal spike effect. The power density per unit depth P is determined by the current density J and the electric field

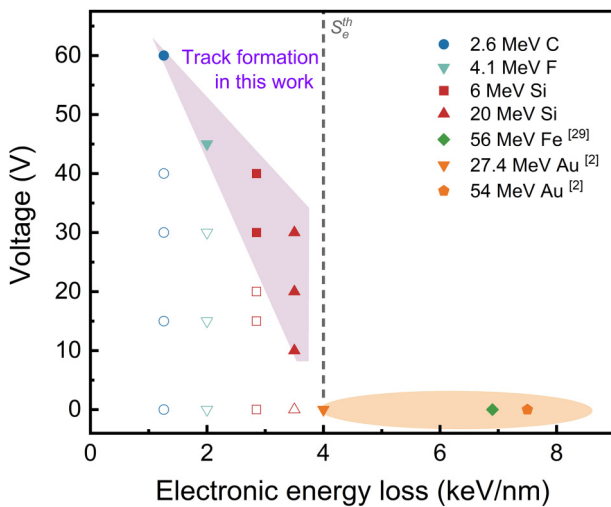


FIG. 5. Experimental results of ion track formation in a-SiO₂ (points) under different electronic energy loss and electric field conditions. Solid points indicate ion track formation, while hollow points indicate no formation.

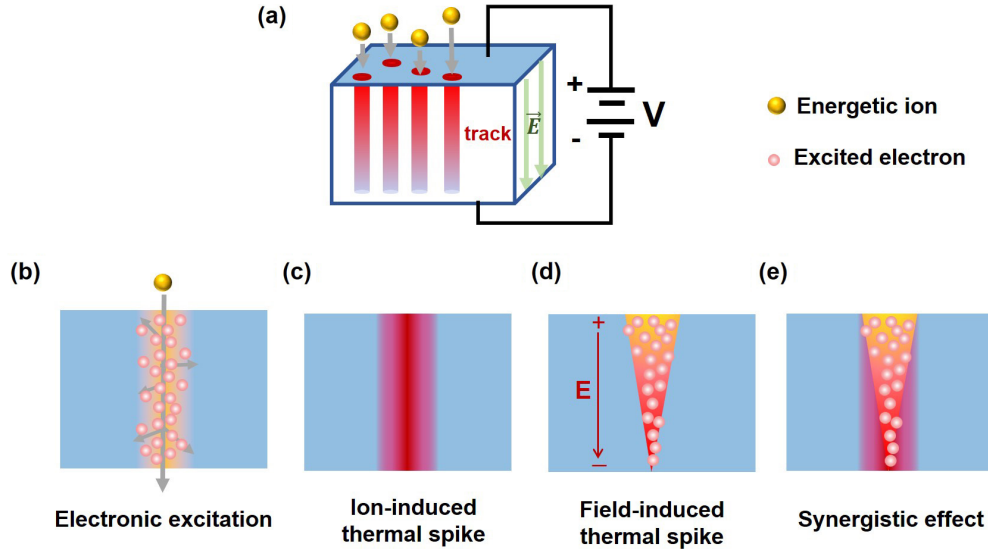


FIG. 6. Schematic diagram of the field-enhanced thermal spike model: (a) track formation in the sample irradiated by energetic ions under electric fields, (b) electronic excitation induced by electronic energy loss, (c) thermal spike generated by ion-induced electronic energy loss, (d) thermal spike generated by field-accelerated electron energy, and (e) synergistic thermal spike effect arising from the coupling of panels (c) and (d).

strength E , written as

$$P = \int J \cdot E dS.$$

The ATSM neglects the electron-phonon coupling process by setting the end of electron-phonon coupling at $t = 0$ and directly prescribing the temperature distribution in the target. This simplification is insufficient for our field-enhanced thermal spike model, where the transfer of heat from ion-induced electronic energy loss and field-induced electron energy to the atomic system must be accounted for. Accordingly, we define the initial time ($t = 0$) as the moment that the incident ion exits the sample and its energy loss has been fully deposited into the solid's electronic system, and then initiate the calculation of the heat transfer process. We extended the conventional thermal spike model by modifying the electron-phonon coupling energy Q to a field-enhanced heat Q^* that encompasses all energy transfer processes under electric-field-enhanced conditions: The following thermal equations govern this process under the synergistic effects of irradiation and applied electric field:

$$Q^* = Q(S_e) + Q(J) = gS_e + \underbrace{\iint J \cdot E dS dt}_{\text{electric-field-induced term}}$$

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \frac{\partial^2 Q^*}{\partial S \partial t}.$$

The Fourier heat conduction equation governs the relationship between the target material's temperature T and the heat transfer Q^* . In insulators (e.g., a-SiO₂), the thermal conductivity κ is small, yielding strong spatial localization of deposited heat and limited lateral dissipation; consequently, high temperatures readily develop around the ion track. Moreover, insulators generally possess weak bonding and low melting

points, which facilitate collective bond breaking and phase transformation at elevated temperatures. In contrast, semiconductors such as Si and SiC exhibit larger κ , stronger bonding, and higher melting points, rendering melt-mediated phase transitions far less probable; metals accentuate these trends. These trends explain why the S_e required for ion track formation increases from insulators to semiconductors to metals.

The intricate nature of electron dynamics presents significant challenges in accurately modeling electron-phonon coupling processes. To address this complexity, we implemented a pragmatic approach that decouples the calculation of electronic energy loss and field-induced energy contributions, treating these energy deposition mechanisms as independent phenomena. In our model, the S_e component is uniformly fed into the system over a characteristic timescale of 150 fs for a-SiO₂ [39], incorporating an electron-phonon coupling coefficient $g = 0.4$ [34,35], to quantify the energy transfer efficiency. Concurrently, the temporal extent of field-induced energy deposition is dynamically determined by electron transport velocities, with the process naturally terminating upon electron migration to boundaries where recombination occurs. Although this methodological separation of electron energy contributions represents a simplification of the actual physics, it renders the synergistic interaction between ion-induced S_e and field-induced electron energy more transparent, as schematically depicted in Fig. 6. Meanwhile, the agreement between our simulations and experiments further supports the validity and practical utility of this simplified modeling approach.

To quantitatively illustrate the subsequent effects of electric-field-enhanced energy deposition, we construct a finite element simulation based on the extended field-enhanced thermal spike model using COMSOL Multiphysics software. This simulation focuses on the temperature response of a-SiO₂ to assess whether the field-enhanced energy deposition

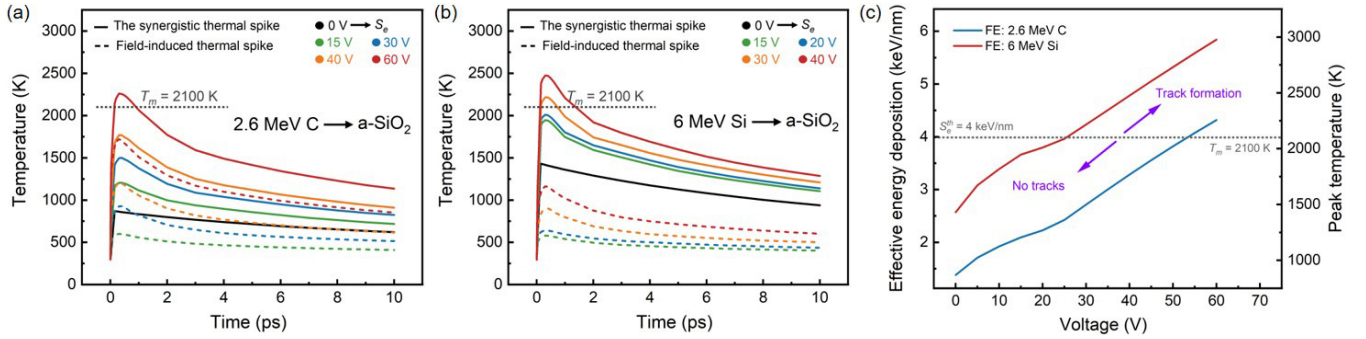


FIG. 7. Field-enhanced thermal spike effect in a-SiO₂. (a), (b) Simulated temperature evolution induced by 2.6 MeV C and 6 MeV Si ions, respectively. Solid lines show synergistic thermal spikes from combined ion and field effects, black solid lines represent conventional free-field cases (S_e only), and dashed lines show thermal spikes from field effects alone. (c) Effective energy deposition (left axis) and peak temperature (right axis) as functions of applied voltage. Gray dotted lines in all panels denote ion track formation thresholds. All results were obtained from FE simulations incorporating the field-enhanced thermal spike model.

method can promote ion track formation and numerically reveals the thermal spike effect under varying bias voltages (electric field intensities) and S_e conditions. Our simulation, referencing the ATSM, assumes that the irradiation-induced electronic energy deposition and the instantaneous electronic excitation follow a Gaussian profile with $a(0) = 4.5$ nm in a-SiO₂ [35]. We take $T_m = 2100$ K (with a phase transition latent heat of 1.14 eV/molecule [2]) as the melting temperature of a-SiO₂, which serves as the criterion for continuous ion track formation. Under zero electric field, the calculated track temperature attains this threshold T_m when $S_e = 4$ keV/nm.

B. Simulation results

The synergistic effect of thermal spikes induced by both incident ions and applied electric fields is key to promoting ion track formation. We performed finite element (FE) simulations with varying electric field strengths under 2.6 MeV C and 6 MeV Si ion irradiation conditions to reveal this enhanced thermal spike effect, with results shown in Figs. 7(a) and 7(b). For the same given irradiation conditions, the contribution of ion-induced electron energy deposition (i.e., electronic energy loss, S_e) to the thermal spike remains fixed (black solid lines in Fig. 7, representing thermal spikes without electric field). The S_e -driven thermal spike increases the target temperature during the 150 fs electron-phonon coupling period; once the electronic energy transfer ceases, the temperature declines. The heat transport follows the Fourier heat conduction equation. While the field-induced electron energy increases with external field strength, it subsequently enhances the thermal spike effect. To determine the contribution of field-induced electron energy to the synergistic thermal spike, we also simulate thermal spikes formed solely by field-induced electron energy (dashed lines in Fig. 7). The results show that field-induced electron energy is sufficiently strong and field-induced thermal spike effects are comparable to or even exceed those of ion-induced thermal spikes. Field-induced electron-lattice energy transfer is complete within 0.3 ps, nearly in sync with the ion-induced thermal spike, enabling a strong synergy between the two energy deposition components. Simultaneously, within such short timescale, electrons propagate only along the ion trajectory (parallel to the

electric field E), with radial diffusion suppressed to a negligible level. Consequently, both energy depositions occur within the same spatial domain. This explains why the electric field enhancement method significantly enhances the confined energy deposition.

Under identical irradiation conditions, leveraging the field-ion synergistic effect, increasing the external electric field strengthens field-induced electronic energy deposition, thereby continuously raising the material's peak temperature. Based on their proportional contribution to thermal spikes, field-induced electron energy can be equivalently treated as an *effective electronic energy loss*, facilitating direct comparison with effective energy deposition E_c . When energy deposition exceeds the threshold, the local temperature of a-SiO₂ will simultaneously exceed the phase transition temperature, successfully forming ion tracks. Figure 7(c) illustrates how energy deposition and peak temperature vary with external electric field under 2.6 MeV C and 6 MeV Si ion irradiation, readily revealing the electric field thresholds required for ion track formation under low- S_e irradiation conditions. Lower S_e means more supplemental energy and fewer excited electrons; thus, a stronger external field is required.

The corresponding E_c^{th} conditions for ion track formation under electric fields obtained from FE simulation are shown in Fig. 8, agreeing extremely well with the experimental data in Fig. 5. With the electric-field-enhanced method, this threshold curve replaces the conventional irradiation S_e^{th} , revealing the pattern of electric-field-enhanced energy deposition, and providing critical mechanistic insights for ion track formation in various solids.

Semiconductor and metallic materials rarely form ion tracks under conventional irradiation, limiting their applications in fields such as nanoscale circuit patterning [40]. However, their superior electron mobility μ_n compared to a-SiO₂ facilitates stronger and more concentrated energy deposition in electric fields. Theoretically, semiconductors and metals could exhibit better electric field regulation effects, forming ion tracks under this proposed method. Additionally, the electric field enhancement method can be extended to other irradiation applications, such as ionization-induced annealing of preexisting defects in various materials [4], offering broad applicability.

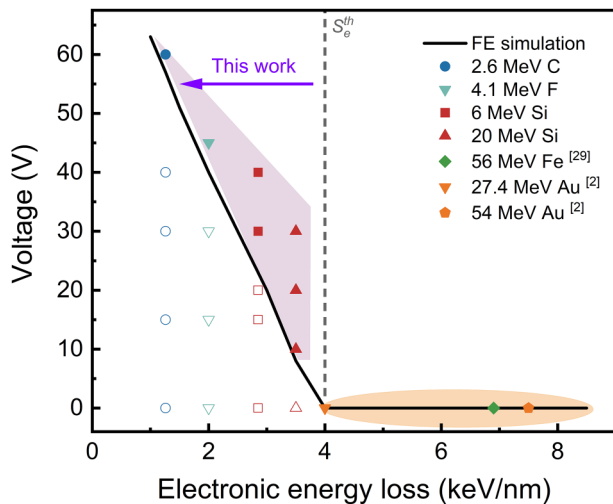


FIG. 8. The track formation criteria (black solid line) obtained from the FE simulation. Solid points indicate ion track formation, while hollow points indicate no formation.

IV. CONCLUSION

In conclusion, this work establishes a method that applies external electric fields during irradiation to enhance nanoscale energy deposition. This method enhances electron-phonon coupling in the critical subpicosecond time frame, enabling control over effects that were previously inaccessible at given irradiation parameters. The field-enhanced method demonstrably promotes ion track formation in a-SiO₂ under low- S_e irradiation by C, F, and Si ions—species for which track

formation in a-SiO₂ has not been previously reported—thereby confirming the method's effectiveness.

We extended the field-enhanced thermal spike model by combining ion-induced electronic energy loss with field-induced Joule heating to elucidate the physical mechanism of this method. Based on this extended model, we first simulated the thermal spike process under electric-field enhancement and then obtained a threshold curve via multiphysics finite-element simulations, which shows excellent agreement with the experimental results. While demonstrated by ion track formation in a-SiO₂, further studies across different materials and irradiation regimes will be essential to fully establish its potential.

Overall, this work opens a research area and fills a theoretical gap in ion-matter interaction. The electric-field-enhanced irradiation method has practical significance and potential applicability for microelectronics research, various nanostructure fabrication, applications of electronic devices in space environments, and so on.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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