Thermal Design Using Two-Dimensional Materials: Invisibility Cloak and Thermal Guiding

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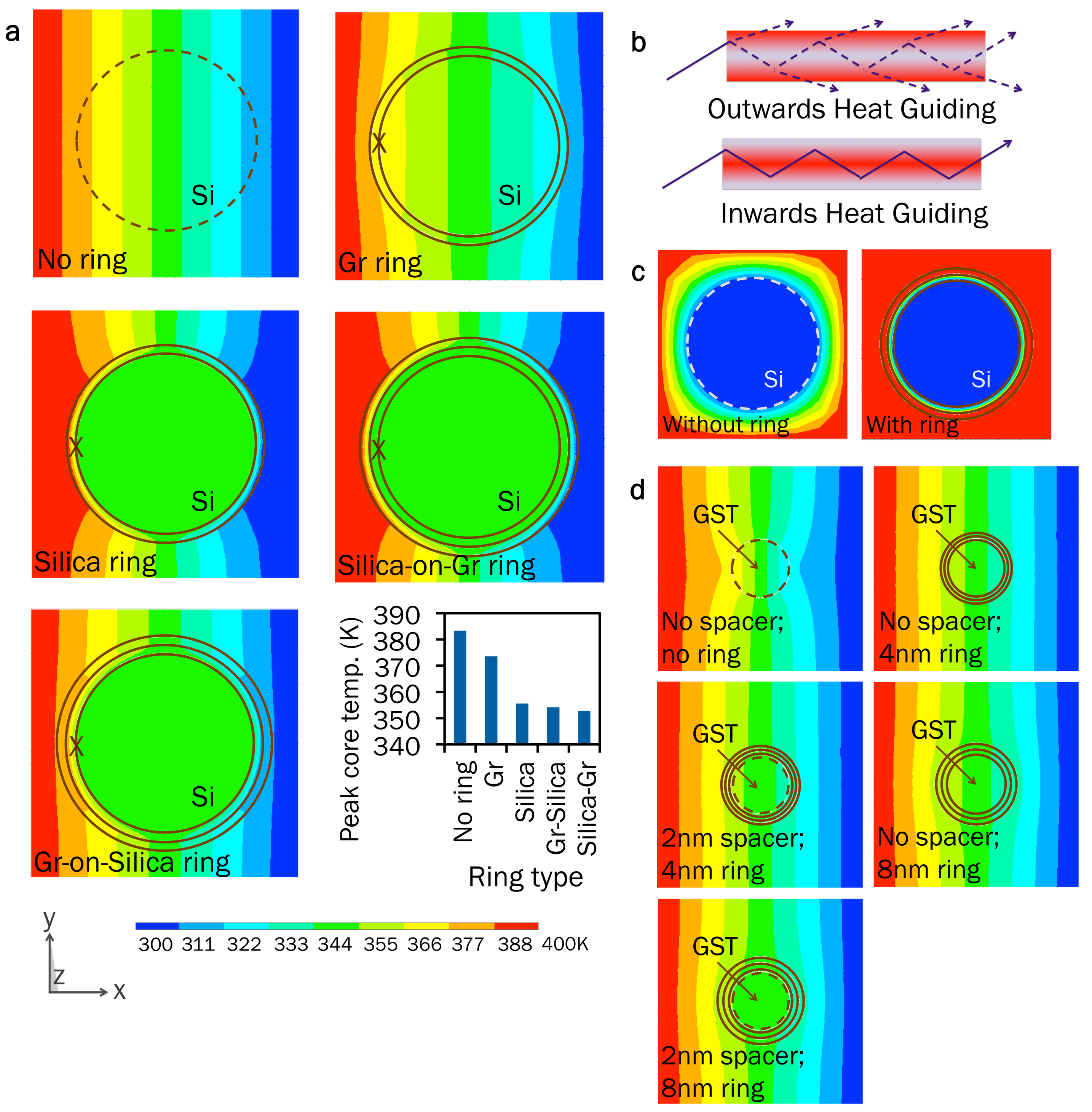
Introduction

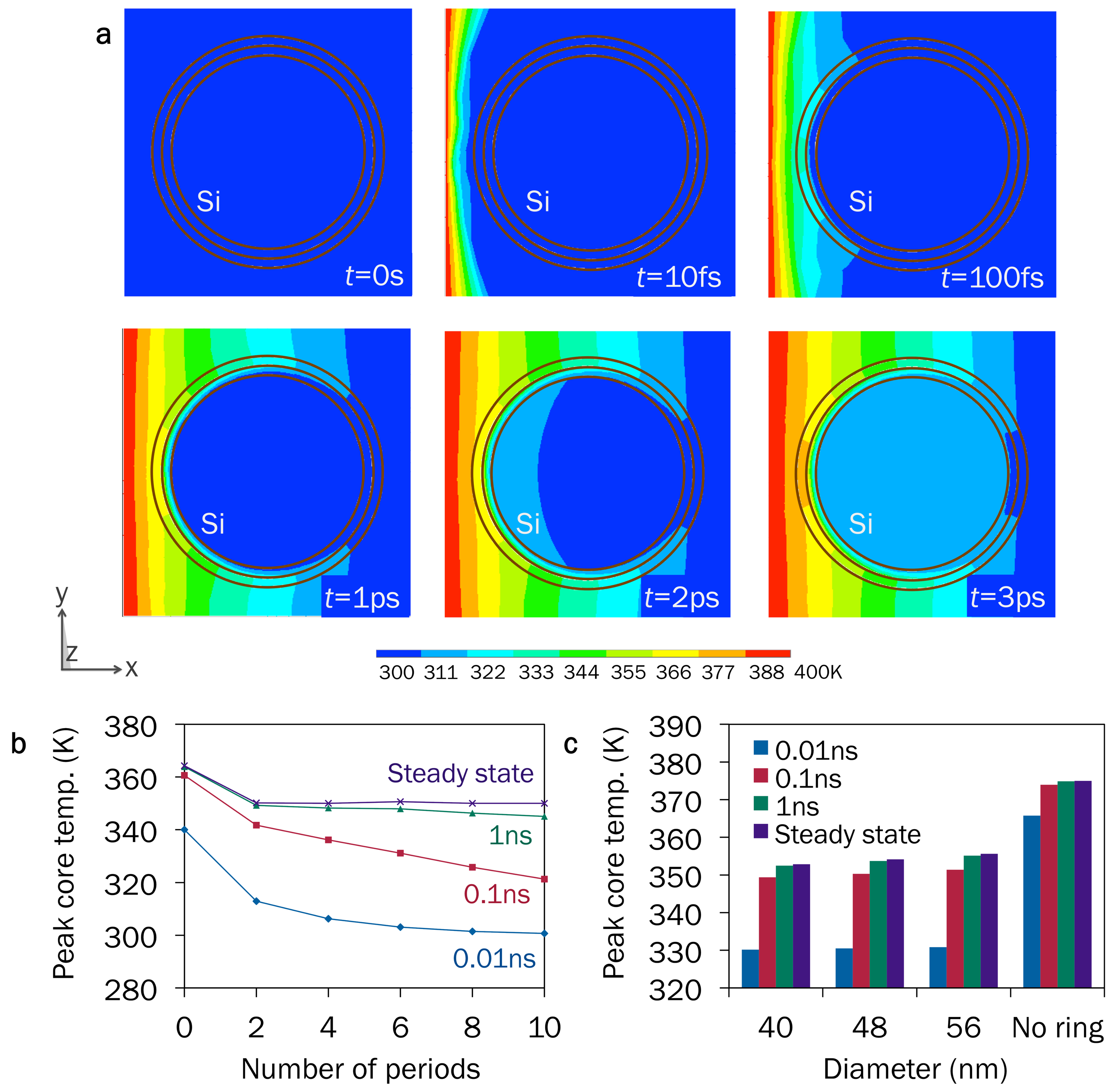
One of the requirements for achieving faster CMOS electronics is to mitigate the unacceptably large chip areas required to steer heat away from or, more recently, towards the critical nodes of state-of-the-art devices. While thermal-guiding (TG) structures can efficiently direct heat vis "meta-materials" engineering, some key aspects of the behaviour of these systems are not fully understood. Here, we demonstrate control of the thermal-diffusion properties of TG structures by using nanometer-scale, CMOS-integrable, graphene-on-silica stacked materials through finite-element-methods simulation.

Results: Heat Shielding Characteristics



Using a temperature-profile (TP) analysis, Si matrices, without thermal guides and with the above thermal boundary conditions, showed only non-uniform temperature distributions across the entire structure, in marked contrast to the silica-ring thermal-guide models, which exhibited rather uniform temperature profiles inside the rings and non-uniform temperature distributions outside the rings.

Results: Time-Dependent Behaviour

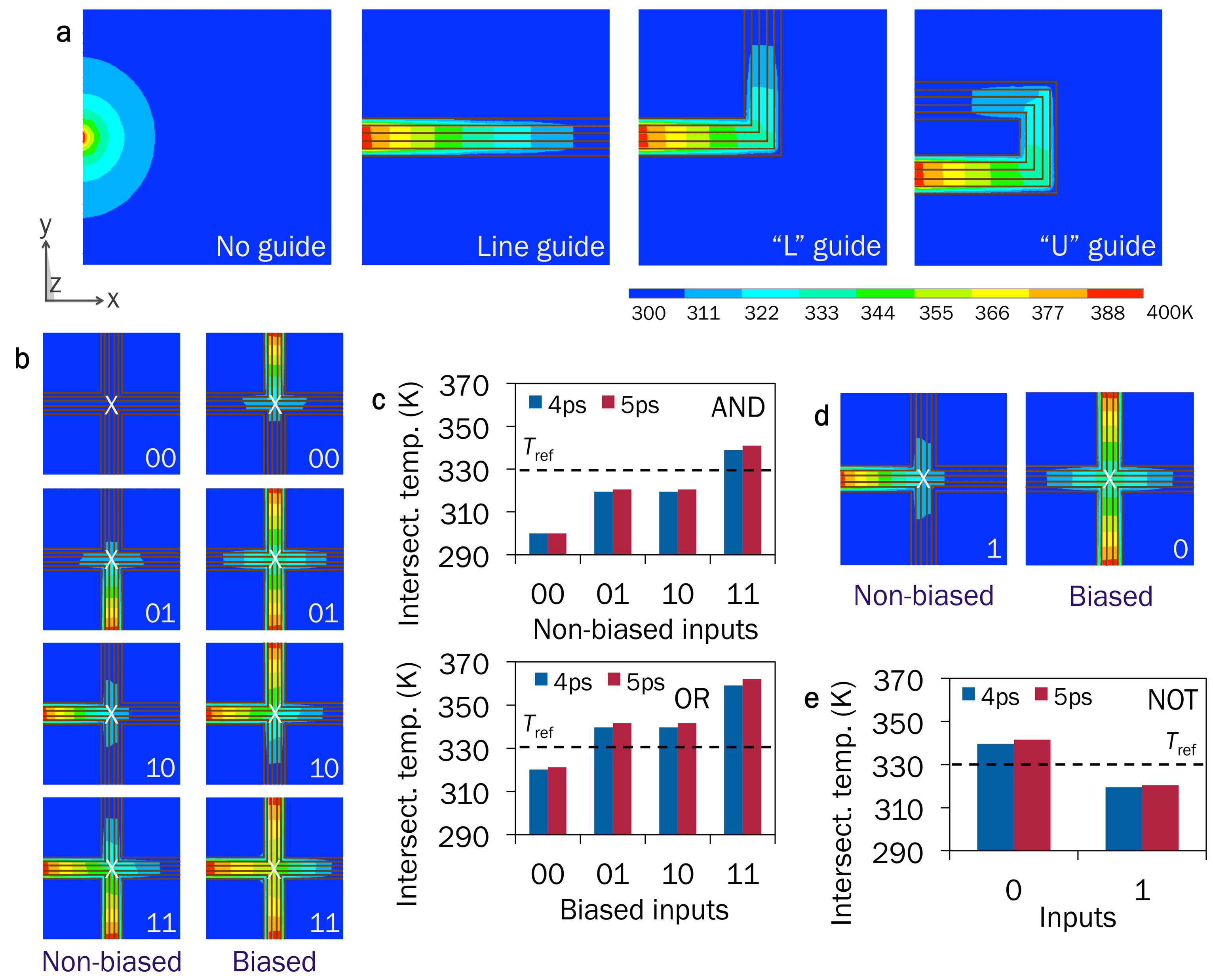


To understand how TG structures were capable of producing various temperature distributions or thermal-cloaking profiles under steady-state simulation conditions, transient simulations of silica- and graphene-based thermal guides in Si matrices were conducted at various time scales.

Discussion

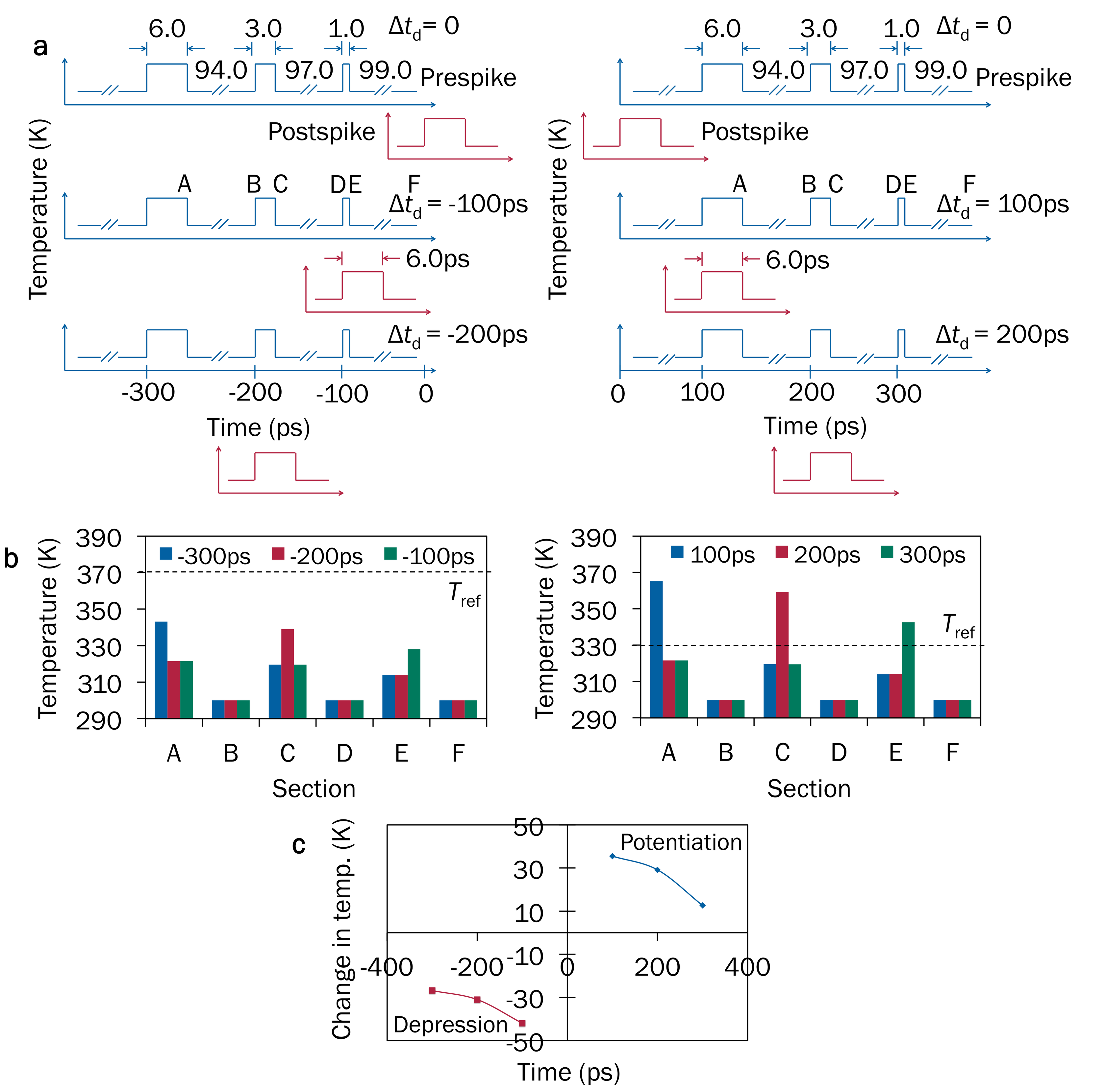
These simulation results suggest that controllable and advanced thermal-switching operations can be produced using thermal guiding with GOS structures. By using thermal guides with a stronger propensity for thermal diffusion, a systematic increase in the contrast of temperature variations could be achieved during switching. Graphene contains a single layer, or a few layers, of *sp*-bonded C atoms arranged in a honeycomb lattice, while silica consists of a connected network of tetrahedra of four O atoms surrounded a central SI atom.

Results: Thermal-Switching Boolean-Logic Operations



To investigate applications of the thermal-diffusion properties of TG structures for varying schemes of excitation, we were further able to perform thermally based Boolean-logic computations on a single structure by comparing two configurations of four-way crossed GOS-guided models, i.e., thermally nonbiased and biased.

Results: Thermally Based STDP-Learning Circuits



Our crossed four-way GOS thermal-guided models were exposed to varying bias setting and spike-timing delays. The boundary conditions were set to a series of 400 K pulses at the left flux-guide boundary for the pre-spike pulses and a single 400 K pulse at the bottom flux-guide boundary for the post-spike pulse. The durations of the pre-spike pulses were chosen to be 6.0, 3.0 and 1.0 ps and the time intervals between the pre-spike pulses were kept constant at 94.0, 97.0 and 99.0 ps. The duration of the post-psike pulse was kept the same at 6.0 ps, and the resulting temperatures at the flux-guide intersection after the application of each pre-spike pulse were analysed. The changes in synaptic weight, Δw, which is given by the difference between the peak intersection temperature T_p, for each spike-timing delay, t_d, and the reference temperature T_{ref}, were recorded (Δw = T_p-T_{ref}; T_{ref} = 360 K for $\Delta t_d < 0$ s; T_{ref} = 330 K for $\Delta t_d > 0$ s)

Conclusion

In this simulational work, we have employed a graphene-on-silica (GOS) stacked material as a model thermal-transport guide to enable thermal cloaking, as well as thermal concentration, of a CMOS-integrable, ultrathin, embedded structure, and which also demonstrates controllable and advanced thermal-switching operations. Use of the simulational approach outlined here could potentially lead to the design of superior TG structures in the future by finding materials, for example, that cool nanometer-size regions for extended periods, or to much lower temperatures, and for the investigation of the effects of thermal guiding, for instance, with chevron-like patterns.

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General Track
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