



Editorial

Manipulating hot carrier cooling in silicon phononic crystals opens new application opportunities



Phononic crystals (PnCs) have had a multiple of important and promising applications such as sonic diodes, acoustic cloaking, optomechanics, and thermoelectrics [1–5]. Undoubtedly, it is of significance to explore new findings for PnCs, which can open new application opportunities.

Recently published in *NPG Asia Materials*, Yan *et al.* observed the experimental evidence of significantly slowed hot carrier cooling in a two-dimensional (2D) silicon PnC by using ultrafast transient absorption measurements [6]. They firstly designed and fabricated 2D silicon structures on the silicon-on-sapphire wafer, where the silicon is an intrinsic monocrystalline thin film with the thickness of 550 nm, epitaxially grown on a thick Sapphire substrate. For comparison, they prepared three samples: (1) the reference, (2) $t=550$ nm, $P=1160$ nm, and $d=1000$ nm, and (3) $t=550$ nm, $P=1160$ nm, and $d=1060$ nm. A tilted-view scanning electron microscope (SEM) image and a top-view SEM image of the fabricated 2D structured crystalline silicon sample are shown in Figs. 1a and b. The transient absorption (TA) spectra of the three samples as a function wavelength were measured and extracted at different probe wavelengths. As an example, the TA kinetics of the three samples at the same single probe wavelength of 1080 nm are shown in Fig. 1c, where the dots are for measurements. To do data analysis, commercial Surface Explorer analysis software is employed to fit the experimental data to assess the hot carrier lifetimes. The fitting results of the three samples are shown in Fig. 1c using lines. The obtained hot carrier cooling times are 0.45, 0.95 and 15.9 ps for the three samples of (1) the reference, (2) $t=550$ nm, $P=1160$ nm, and $d=1000$ nm, and (3) $t=550$ nm, $P=1160$ nm, and $d=1030$ nm. By comparison, they show that the 2D silicon structure with $d=1060$ nm demonstrates the largest lifetime improvements with tens of times than the other two cases. In order to find the possible reasons, the frequency band structures of the three samples were calculated by using *Comsol Multiphysics* software. The results show that a phononic bandgap exists in the sample with $d=1060$ nm (Fig. 1d) while there are no phononic bandgaps in the other two samples.

The experimental result indicates that the existing application range of phononic crystals can be broadened from previous applications to new applications. Manipulating hot electrons with harvesting kinetics is an important avenue to develop promising applications such as ultrahigh-efficiency solar cells, photodetectors, photocatalysis, and spectral range [7–11]. As a result, new opportunities are offered by the present Si PnCs. As a promising application example, we calculate and assess the limiting cell efficiency for

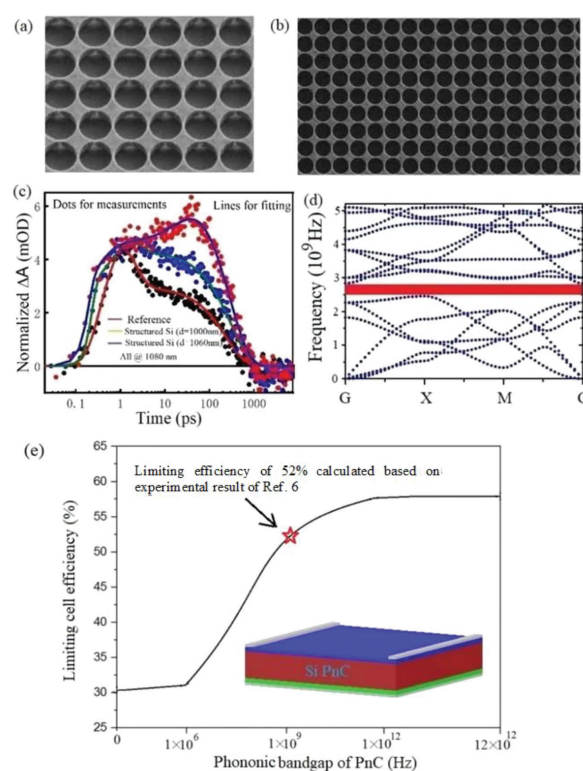


Fig. 1. (a) A tilted-view SEM image of the 2D nanostructured silicon, where $d=1060$ nm and $P=1160$ nm. (b) A top-view SEM image of the 2D structured silicon with $d=1060$ nm and $P=1160$ nm. (c) The TA kinetics of the three samples: all samples at probe wavelengths of 1080 nm. Dots represent the measurements and lines represent the fittings. (d) Calculated band structure of the sample with $d=1060$ nm, where the red band represents the phononic bandgap. (e) Estimated limiting cell efficiency as a function of phononic bandgap of a silicon PnC, where the inset is a schematic of a PnC solar cell with energy selective contacts. The star represents the calculated efficiency based on the silicon nanostructure sample with $d=1060$ nm. (a–d) Adapted with permission [6]. Copyright 2022, Springer Nature.

the present 2D silicon PnCs for photovoltaics as a function of frequency phononic bandgap. A schematic of a proposed silicon PnC solar cell is shown in the inset of Fig. 1e. Here, a single-junction solar cell of crystalline silicon bandgap $E_g=1.12$ eV is considered in the present model under typical conditions, *i.e.*, standard test

conditions with unconcentrated illumination. Note that in the present limiting efficiency calculations, we assume that within hot carrier cooling time, the generated hot carriers in the absorber can be timely extracted by appropriate energy selective contacts. The calculated phononic bandgap dependent limiting cell efficiency and the limiting efficiency based on the experimental result [6] are shown in Fig. 1e. It can be seen from Fig. 1e that the maximum limiting efficiency is 58%, which is twice as high as the Shockley-Queisser (S-Q) efficiency limit of 29.4% for conventional silicon solar cells. In addition, it is also found that the limiting efficiency based on the experimental result [6] with $d = 1060$ nm is approximately 52%, which is still far beyond the S-Q efficiency limit of 29.4%.

The promising application toward ultrahigh efficiency silicon solar cells is significant because crystalline silicon photovoltaics occupy the global photovoltaic market share of 95%. Currently, the world record efficiency 26.81% of silicon solar cells is approaching to the S-Q limit of 29.4%. It means that it is necessary and urgent to study new strategies/methods to achieve ultrahigh efficiency exceeding the S-Q limit. Currently, a possible scheme is using the silicon/perovskite tandem solar cells with the strategy of multi-junctions to exceed the S-Q limit. But, the perovskite solar cells suffer many grand challenges and uncertainties. For example, notorious instability of perovskite solar cells seriously hinders its commercialization process. In contrast to the silicon/perovskite tandem cells, the silicon PnC solar cells utilize the excess energy of photons ($E_{ph} > E_g$) achieving ultrahigh efficiency in a single junction, which is fundamentally a different strategy. Furthermore, a unique feature of silicon is outstanding stability, which can guarantee the solar cell lifetime of 25–30 years at least.

In summary, this work presents a comment/mini-perspective that hot carrier cooling can be manipulated in two-dimensional silicon PnCs. It will open new opportunities for promising applications in the areas of ultrahigh-efficiency solar cells, photodetectors, photocatalysis, and spectral range. As an example, the silicon PnC's potential for photovoltaic application is analyzed and discussed.

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Available online 13 March 2023

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