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Thermal conductivity reduction in $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ high entropy carbide from extrinsic lattice defects

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ABSTRACT

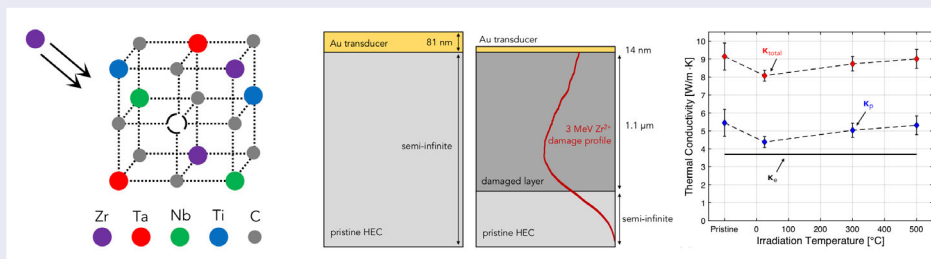
High entropy carbides ceramics with randomly-distributed multiple principal cations have shown high temperature stability, low thermal conductivity, and possible radiation tolerance. While chemical disorder has been shown to suppress thermal conductivity in these materials, little investigation has been made on the effects of additional, extrinsically-generated structural defects on thermal transport. Here, $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ is exposed to Zr ions to generate a micron-scale, structural-defect-bearing layer. The reduction in lattice thermal transport is measured using laser thermoreflectance. Conductivity changes from different implantation temperatures suggest dislocation loops contribute little to phonon scattering while nanoscale defects serve as effective scatterers, offering a pathway for thermal engineering.

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KEYWORDS

High entropy ceramic; defects; thermal transport



1. Introduction

High entropy carbide ceramics (HECs) have emerged in the last several years as a promising class of materials for applications involving high temperatures or other environmental extremes. Borrowing from the maturing field of complexity-engineering and entropic-stabilization in metal alloys [1], new high entropy ceramics with complex selections of cations have emerged across oxides, borides, nitrides, sulfides, silicides, and carbides [2,3]. HECs, in particular, have been synthesized as bulk specimens and as thin films and have been shown to have a variety of physical characteristics attributed to the presence of a disordered cation sublattice including high hardness [4–6], low thermal conductivity [7,8], oxidation resistance [9–11], and radiation tolerance [12].

To date, experimental studies of the thermal transport characteristics of these HEC materials have been relatively few and primarily focused on five-cation chemistries including $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Nb}_{0.2}\text{Ti}_{0.2})\text{C}$ [7,8,13] and $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Mo}_{0.2}\text{W}_{0.2})\text{C}$ [8]. These studies have exclusively focused on the thermal transport characteristics of as-synthesized materials in addition to their resulting structure. While some progress has been made in computationally treating transport in these systems, large discrepancies exist in the estimation of the lattice contribution to thermal conductivity between simulation and experiment [14]. While noted as a promising feature of these systems, the ability to thermally engineer HECs for targeted applications has not yet been exploited in a systematic manner.

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In particular, the interplay between chemical disorder, stoichiometry, and *structural defects* in relation to thermal transport has yet to be explored in HECs or, to a large extent, in any high entropy ceramic. Frameworks for understanding the effects of structural defects, and tailoring performance by extrinsically introducing such defects, are well-established for single-principal-element materials and compounds [15,16]. Effects on electron and phonon thermal conductivity are routinely expressed in terms of the scattering strength of structural defects of particular types including 0D point defects, 1D dislocations, 2D dislocation loops or boundaries, and 3D inclusions [17–20]. However, how thermal carriers scatter from each of these classes of structural features in the limit of maximized chemical disorder is not yet well understood. For HECs in particular, the relative partitioning of these thermal carriers (electrons and phonons) depends sensitively on stoichiometry [8] and introduces additional challenges for developing a complete understanding of transport phenomena. However, controlling carrier partitioning, therefore, could also eventually serve as a tool to engineer thermal properties.

Here, the coupled effects of chemical disorder and extrinsically-imposed lattice defects are studied in $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$. This four-cation HEC was originally synthesized Hf-free by Wang and coworkers to study its potential, if any, for use in nuclear systems, as Hf has a large neutron absorption cross section [12]. Specimens of $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ were exposed to Zr ion beam irradiation to generate a micron-scale defect-bearing layer at the surface of bulk specimens at a series of different temperatures. Following exposure, a spatial domain thermal reflectance (SDTR) method is used to determine the total thermal conductivity of the defect-bearing region using a multi-layer thermal transport model. A combination of SDTR and electrical resistivity measurements on a pristine bulk HEC are used to determine the total heat capacity and estimate the electron contribution to thermal conductivity. The resulting thermal performance is interpreted in the context of previously-measured concentrations of defects from electron microscopy, showing that dislocation loops serve as much less effective thermal scatters in these chemically disordered structures than would be expected from classical phonon scattering theory.

2. Materials and methods

The $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ specimens investigated in this work have been described previously [12], so only a brief summary of their synthesis and ion beam processing will be described here. Bulk specimens were fabricated from commercial powders of the constituent

Table 1. Measured dislocation loop diameter and density in Zr-ion irradiated HECs at different temperatures from Wang and coworkers [12]. Averages of the spatially-heterogeneous loop microstructure are given here as a relative comparison between different irradiation temperatures.

Irradiation Temperature	Ion Fluence	Ave. Loop Diameter [d_l]	Ave. Loop Density [n]
25°C	8×10^{15} ions/cm ²	1.6 nm	9.5×10^{17} loops/cm ³
300°C	8×10^{15} ions/cm ²	2.0 nm	7.4×10^{17} loops/cm ³
500°C	8×10^{15} ions/cm ²	2.1 nm	6.0×10^{17} loops/cm ³

binary carbides through ball milling the as-received powders and consolidation with spark plasma sintering (SPS). Scanning electron microscopy indicated an as-synthesized mean grain size of 19 μm . X-ray diffraction patterns of as-synthesized specimens are indexed as a single-phase rock-salt structure, similar to other multi-cation carbides [12]. The theoretical density is calculated from the XRD lattice constant as 8.46 g/cm³ and the measured density of the bulk materials is 8.25 g/cm³, resulting in a relative density of 97.5%. Mechanically polished specimens were exposed to 3 MeV Zr^{2+} ions to a total fluence of 8.0×10^{15} ions/cm² at three temperatures, 25, 300, and 500°C. Ions at this energy generate structural defects over an $\sim 1.5 \mu\text{m}$ depth at the sample surface, with peak defect production at $\sim 800 \text{ nm}$ [21,22]. Extensive transmission electron microscopy (TEM) characterization by Wang et al. showed the generation of a population of both perfect and faulted Frank loops with consistently small diameters ($\sim 2 \text{ nm}$) at all three temperatures, with density peaking near the peak defect generation region, and no other visible defects [12]. A spatially-averaged summary of the measured dislocation loop size and density is listed in Table 1, noting that no loops were observed in the as-synthesized material. No radiation-induced chemical segregation was observed near the grain boundaries for the as-synthesized or irradiated materials.

For both pristine and ion irradiated $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$, SDTR is used to extract thermal properties including thermal conductivity, κ , thermal diffusivity, D , and, in the case of the as-synthesized material, the specific heat capacity, C_p . In SDTR, periodic local temperature variations are induced using an intensity-modulated 660 nm CW heating laser and detected using a 532 nm CW probing laser through the thermoreflectance effect [23,24]. The heating and probing lasers are both focused to spot sizes on the order $\sim 1 \mu\text{m}$ using a high-power optical objective and the probing laser scanned across a distance of $\sim 20 \mu\text{m}$ centered on the heating spot. By coating specimens with thin transducer layers of gold, a strong thermoreflectance response at 532 nm

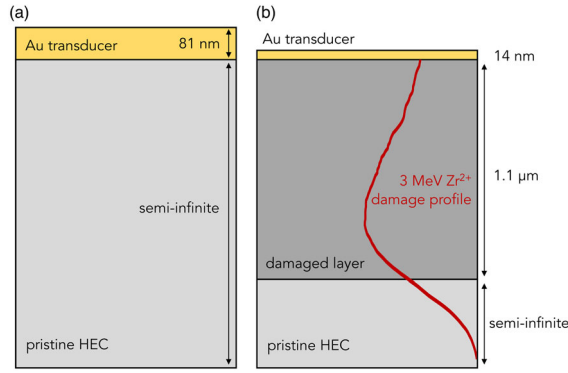


Figure 1. Thermal layering model used for pristine (a) and ion irradiated (b) HECs, overlaid with the defect generation profile from Zr ion implantation. The thick gold transducer layer used on the pristine specimen allows for all three thermal parameters, κ , D , and C_p , to be extracted from the two-layer thermal model. The defect generation profile and ion irradiated layer are to scale, while the gold transducer thicknesses are not.

is ensured. The relative phase lag between the heating and probe laser as a function of separation distance at several modulation frequencies in the range 5–100 kHz is recorded using lock-in detection [23]. A multi-layer thermal model taking into account the thermal properties of an arbitrary number of layers using the thermal quadrupole method is used to return best-fit values for the properties of selected layers [25,26].

The thermal layering model used for pristine and as-irradiated ($\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25}\text{C}$) is shown in Figure 1. For pristine specimens, Figure 1(a), a relatively thick 81 nm Au film was deposited in order to achieve the highest joint sensitivity to thermal conductivity and thermal diffusivity based on analysis shown in the Supplementary Material. With known density, independent optimization of both κ and D allows C_p to be determined as $C_p = \kappa/D\rho$, where ρ is the mass density. For all SDTR analysis, the theoretical density is fixed for analysis as scans on the order of 20 μm remain largely intragranular. In addition, differential scanning calorimetry (DSC) measurements of C_p are made independently on pristine ($\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25}\text{C}$) to confirm the value inferred through SDTR.

For ion-irradiated samples, Figure 1(b) shows the three-layer thermal model overlaid with spatially-varying SRIM-calculated profile of displacement damage. Previous investigations of ion-implanted materials using SDTR and other thermoreflectance approaches have proposed various methods for the determining the most appropriate layer segmentation for continuously spatially heterogeneous material volumes [26,27]. Over-segmenting this defect-bearing layer leads to an ill-posed inverse problem, causing issues of uniqueness

and sensitivity in the fitted solution. As such, a three-layer thermal model was used here with the thickness of the ion-modified layer fixed at 1.1 μm for all conditions. This distance corresponds to half the maximum value of the displacement damage near the end of range. For the three-layer model, C_p is assumed constant for both defect-bearing and pristine layers, as there is little evidence to suggest that heat capacity is meaningfully affected by structural defects. In each optimization, the thermal parameters of the pristine substrate layer are fixed to those measured independently on the pristine specimen and D and κ optimized self-consistently for the defect-bearing layer. A table of the fixed and varying optimization parameters used in the two- and three-layer models are detailed in the Supplementary Materials.

To ensure this parameterization results in the highest sensitivity to the thermal properties of the defect-bearing layer, a detailed sensitivity analysis is carried out, see Figure 2. Relative sensitivity is calculated for D and κ of the irradiated layer, the thickness of the irradiated layer, and the thickness of the gold transducer film as

$$S(\xi) = \frac{\varphi(\xi + \Delta\xi) - \varphi(\xi)}{(\Delta\xi/\xi)}, \quad (1)$$

where $\varphi(\xi)$ is the spatially-varying thermal phase delay and ξ is the parameter in question. Figure 2 is calculated for a baseline set of parameters $D = 3.70 \text{ mm}^2/\text{s}$ and $\kappa = 9.14 \text{ W/m} \cdot \text{K}$ for the pristine materials, with a 10% reduction in D and κ in the defect-bearing layer, and assuming a 14 nm thick deposited gold film (with corresponding thermal conductivity [28,29]). An $\sim 10 \text{ nm}$ gold film was chosen as the set point as the sensitivity to a ‘sandwiched’ thermal layer is higher when the transducer layer is thin; 14 nm was eventually deposited on these irradiated samples. As can be seen in Figure 2, the highest sensitivity at both the intermediate and highest modulation frequencies used, 20 kHz and 100 kHz, is to the thermal properties of the defect-bearing layer. Only very weak sensitivities to the precise gold coating thickness and segmented irradiated layer thickness are observed. Together, these sensitivities ensure that the values reported from the three-layer optimization are representative of the defect-modified thermal characteristics.

Total thermal conductivity as measured in these carbide ceramics contains contributions from both electron and lattice (or phonon) thermal transport [8]. To extract the relative contribution of electrons to thermal conductivity, the electrical resistivity of the un-coated side of the pristine bulk ($\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25}\text{C}$) specimen was measured using a 4-point probe. Traditionally, the electrical resistivity can be used to estimate the electronic thermal conductivity as $\kappa_e = LT/\rho_e$, where most commonly $L = L_0 = 2.44 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$ is the

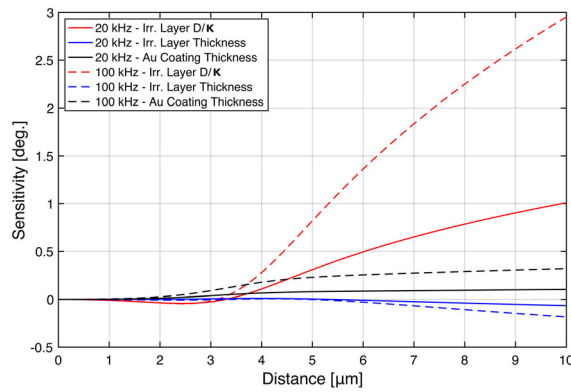


Figure 2. Sensitivity of the three-layer thermal model to several parameters at both 20 kHz and 100 kHz thermal wave modulation frequencies in terms of phase delay difference as a function of SDTR scan distance, the distance between heating and probe laser spots. Initial parameters are taken as 14 nm of Au coating, fixed values of semi-infinite substrate thermal properties, and a 10% reduction in conductivity in the middle, defect-bearing layer. To ensure a constant heat capacity, the values of D and κ in the defected layer are changed in the same proportion in this analysis. Of these parameters, the highest sensitivity is to the thermal properties of the layer of interest.

Lorentz number and ρ_e is the electrical resistivity. However, in single-element metal carbides, L_0 has been shown to overestimate κ_e , such that an effective Lorentz number as calculated by Makinson should be used [8,30,31]. A description of the 4-point probe measurements as well as the conversion of ρ_e to κ_e is provided in the Supplementary Materials. From κ_e and the measured total thermal conductivity, κ_{tot} , the phonon thermal conductivity can be estimated as $\kappa_p = \kappa_{\text{tot}} - \kappa_e$. The relative electron contribution to κ_{tot} has been shown to be a sensitive function of carbon stoichiometry, and therefore bonding character, in binary carbides and these HECs [8,32]. The carbon stoichiometry of as-synthesized $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ is estimated using X-ray photoemission spectroscopy (XPS) to place measured values of κ_e in context. As extraction of the electrical resistivity of solely the defect-bearing layers in the irradiated materials was not possible from bulk specimens, κ_e is assumed to be constant for the defect-bearing material for this initial investigation. This practical limitation will lead to an overestimation of the lattice thermal conductivity reduction, as both electrons and phonons are known to scatter from point defects in refractory carbide and nitride ceramics [31].

3. Results and discussion

SDTR measurements of pristine $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ with a thick gold transducer return room-temperature thermal property values of $k_{\text{tot}} = 9.14 \pm 0.20 \text{ W/m} \cdot \text{K}$

Table 2. Comparison of thermal properties for 4- and 5- component bulk HECs. D and κ are measured for the 4-cation HEC using SDTR and the resulting C_p calculated, while Yan and coworkers used laser flash to measure D , DSC to measure C_p , calculated κ for the 5-cation HEC.

	D [mm^2/s]	κ_{tot} [$\text{W/m} \cdot \text{K}$]	C_p [$\text{J/kg} \cdot \text{K}$]
4-cation ^a	3.70	9.14	293
5-cation ^b	3.60	6.45	191

^a $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$

^b $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Nb}_{0.2}\text{Ti}_{0.2})\text{C}$ [7]

and $D = 3.70 \pm 0.06 \text{ mm}^2/\text{s}$, which imply a specific heat capacity of $C_p = 293 \pm 4 \text{ J/kg} \cdot \text{K}$, with all uncertainties listed as the standard error of multiple spatially-varying measurements. Although no direct comparisons exist for this 4-cation HEC in the literature, these values are consistent with the thermal properties measured in bulk $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Nb}_{0.2}\text{Ti}_{0.2})\text{C}$ synthesized using the same procedure [7]. Table 2 compares the as-measured values of the 4- and 5-cation HEC thermal properties. That the 4-cation HEC measured here retains a higher thermal conductivity is consistent with the lower levels of mass and force constant scattering expected with one fewer principal elements. In addition, the distinctly higher value for C_p is consistent with excluded cation, Hf, having the lowest C_p of any of the constituent binary carbides [7]. Confirmation measurements of C_p made using DSC returned a value $310 \pm 5 \text{ J/kg} \cdot \text{K}$ at $\sim 335 \text{ K}$, consistent with the theoretically monotonically-rising heat capacity in refractory carbides in this temperature range [33].

4-point probe measurements indicated that pristine $(\text{Zr}_{0.25}\text{Ta}_{0.25}\text{Nb}_{0.25}\text{Ti}_{0.25})\text{C}$ specimens have an electrical resistivity $\rho_e = 149 \pm 2 \mu\Omega \cdot \text{cm}$. This is higher than that of binary carbides such as TiC and TaC (68 and $25 \mu\Omega \cdot \text{cm}$, respectively [34]), similar to that for $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Nb}_{0.2}\text{Ti}_{0.2})\text{C}$ reported as $\sim 115 \mu\Omega \cdot \text{cm}$ by Wen and coworkers for sintered pellets [13], but lower than the range reported for thick films of $(\text{Hf}_{0.2}\text{Zr}_{0.2}\text{Ta}_{0.2}\text{Mo}_{0.2}\text{W}_{0.2})\text{C}_{1-x}$ by Rost and coworkers as a function of carbon stoichiometry as $\sim 200\text{--}1200 \mu\Omega \cdot \text{cm}$ [8]. That the measured resistivity is low compared to the range reported for precisely carbon-controlled HECs implies the final, as-synthesized bulk samples are possibly carbon deficient and retain some metallic bonding that would not be present in a perfectly stoichiometric compound. From ρ_e , κ_e is estimated as $3.7 \text{ W/m} \cdot \text{K}$, indicating that 40% of the thermal conductivity is due to electrons in the as-synthesized material and 60% is due to the lattice. From XPS measurements, the metal to carbon ratio is $\text{M:C} \simeq 1$, as detailed in the Supplementary Materials, indicating that an approximately stoichiometric carbide has been maintained. While Rost and coworkers reported generally higher resistivity for stoichiometric

compounds, the deposition of excess, non-metal-bonded carbon in sputter deposited materials complicates a direct comparison [8]. Further correlated microscopy and XPS should be carried out in the future on bulk, sintered ceramics to more fully characterize possibly heterogeneous carbon stoichiometry following synthesis. To ensure that thermal property measurements account for any such variability, ten or more randomly-selected spatially varying measurements are made on each specimen prior to reporting statistical averages.

Using the three-layer thermal transport model as described above, Figure 3(a) shows the total and phonon thermal conductivities as a function of irradiation temperature for the fixed ion fluence applied to each specimen. The electronic contribution is plotted as the constant value estimated for the as-synthesized material. The general trend of a larger decrease in thermal conductivity at lower irradiation temperatures is consistent with expectations from most material systems where extrinsic structural defect production is driven by radiation bombardment. Namely, higher irradiation temperatures increase the mobility and therefore the recombination of any Frenkel defects or small clusters generated by displacement damage, leaving fewer thermal scattering sites [28,35,36]. Using the simplified assumption that κ_e is unaffected by structural defects and the entire reduction is due to phonon scattering, the fractional reduction in lattice thermal conductivity is plotted in Figure 3(b). With this simplified assumption that κ_e is unaffected by radiation-generated defects, an $\sim 20\%$ reduction in κ_p is observed at 25°C , with very little, if any, reduction for exposure at 500°C .

The behavior of the lattice thermal conductivity in the presence of these structural defects is most easily explored using the simplified Klemens-Callaway-Debye model where

$$\kappa_p = \frac{1}{3} \int_0^{\omega_{\max}} d\omega C(\omega) v_g(\omega)^2 \tau(\omega), \quad (2)$$

and $C(\omega)$, $v_g(\omega)$, and $\tau(\omega)$ are the phonon-frequency-dependent heat capacity, group velocity, and relaxation time, respectively [37]. The overall relaxation time is normally considered as a combination of different scattering mechanisms, phonon-phonon scattering, impurity scattering, etc., as summed using Matthiessen's rule. Classical models have been used with success to describe scattering from both perfect (pl) and faulted (fl) dislocation loops in terms of the density and average size of the dislocation loops present as

$$\tau_{pl}^{-1} \propto n d_l \omega^2, \quad (3)$$

and

$$\tau_{fl}^{-1} \propto n d_l^2 \omega^2, \quad (4)$$

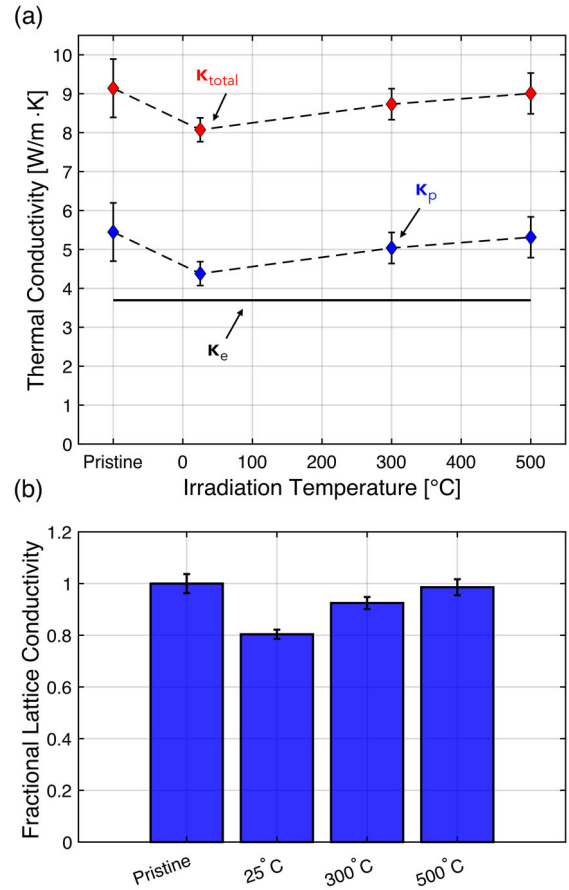


Figure 3. (a) Total, electronic, and phonon thermal conductivity for the pristine HEC and at each of the three ion exposure temperatures. A constant electronic thermal conductivity, κ_e , as measured on the pristine specimen is subtracted from the measured κ_{total} to recover κ_p . (b) Fractional lattice conductivity retained at each ion irradiation temperature. As highlighted, approximately 20% of the lattice thermal conductivity is lost when irradiated at 25°C to this fluence level, while the majority of the lattice conductivity is retained for 500°C irradiations. Error bars in (a) are shown as the standard deviation, σ , of $N = 10$ or more spatially-varying measurements per condition to show the spread in collected data and in (b) are shown as the standard error, $\sigma/\sqrt{N}$, of that sampling set to reflect the overall confidence in the measured value.

where n is the dislocation loop density and d_l is the loop diameter, with each relationship containing prefactors, not shown here, to maintain the correct dimensionality [16]. As Wang and coworkers showed that some number of both perfect and faulted loops were present in these specimens [12], it is useful to compare the products $n d_l$ and $n d_l^2$ to compare the relative effects of extrinsic dislocation loops on κ_p . This comparison is shown in Table 3 and demonstrates that scattering from either perfect or faulted dislocation loops should be nearly identical in each of the three specimens with extrinsic structural defects measured here.

This theoretically identically scattering strength from loops, coupled with the similarly in thermal conductivity

Table 3. Comparison of the phonon scattering rate dependency on dislocation loop size and density for both perfect and faulted dislocation loops. Both scattering rates share a common ω^2 phonon frequency dependence.

Irradiation Temperature	Perfect [nd_l]	Faulted [nd_f^2]
25°C	$1.52 \times 10^{-3} \text{ 1/nm}^2$	$2.43 \times 10^{-3} \text{ 1/nm}$
300°C	$1.48 \times 10^{-3} \text{ 1/nm}^2$	$2.96 \times 10^{-3} \text{ 1/nm}$
500°C	$1.26 \times 10^{-3} \text{ 1/nm}^2$	$2.64 \times 10^{-3} \text{ 1/nm}$

between the pristine sample and that exposed at 500°C, implies that dislocation loops are effectively not scattering phonons in this chemically complex ceramic. This conclusion is reached by noting that at 500°C, few residual point defects are expected following irradiation given the increased defect mobility at high temperatures. These data suggest, therefore, that the interactions between phonons and dislocation loops is inherently distinct in materials with a high degree of chemical complexity compared with traditional ceramics. Analytical dislocation loop scattering models, after Klemens, propose that the long-range strain field associated with dislocations is responsible for the majority of phonon scattering [18,38]. Here, in a maximally-chemically disordered carbide ceramic, dislocations appear to contribute little to phonon scattering, implying their strain fields are suppressed. This long-range suppression could occur as a result of the inherit strain associated with the disordered cation sublattice, although further experimental and computational work is required to investigate these effects directly.

Even though the reduction in κ_p is likely overestimated here due to assumption of constant κ_e across exposure conditions, electrons scatter little from extended loops. Therefore, the conclusion that residual nanoscale structural defects are the primary contributors to conductivity reduction remains unchanged. Altogether, that lattice thermal conductivity is reduced by $\sim 20\%$ at 25°C, in a microstructure expected to contain a high density of both nanoscale and extended defects, supports the conjecture that heat carrier scattering from extrinsic nanoscale defects (point defects and small clusters below TEM resolution) can be used as a tool with which thermal conductivity may be engineered in these systems. Although ion beam irradiation was used to generate extrinsic structural defects in this work, other post-synthesis processing treatments could similarly be used for such defect injection and thermal engineering in the future.

4. Conclusion

Here, the impact of lattice defects extrinsically-generated using ion irradiation on thermal transport in a chemically complex carbide ceramic with four principal cations

has been systematically studied using a laser thermoreflectance technique. Multi-layer thermal modeling allows the defect-affected thermal conductivity of a micron-thick damaged layer generated by ion implantation to be measured. Additional electrical resistivity measurements on as-synthesized material shows that this HEC has a thermal carrier partitioning, between electrons and phonons, in line with that previously observed in similar materials. The reduction in thermal conductivity is observed to be greatest in materials irradiated at low temperatures where a significant population of retained nanoscale defects is expected. At high temperatures, however, little reduction in overall or phonon thermal conductivity is observed. Coupled with prior investigations showing that small dislocation loops have formed under these exposure conditions at all temperatures, these observations indicate that dislocation loops are contributing little to phonon scattering, likely due to a suppression of their long-range strain fields. Nanoscale defects still serve as effective scatterers of thermal carriers in this system, opening a pathway for controlled thermal transport engineering in the presence of maximized chemical disorder in high entropy ceramics.

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Disclosure statement

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