





Development of a high-temperature (295–900 K) Seebeck coefficient Standard Reference Material

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We report the development of a high-temperature Seebeck coefficient Standard Reference Material (SRM) for use in instrument validation and interlaboratory data comparison in the temperature range of 295–900 K to support the research, development, and production of materials and devices related to thermoelectric-based energy conversion applications. We describe the synthesis, anneal–quench procedure, and physical characterization of a *p*-type boron-doped polycrystalline silicon–germanium alloy with a nominal composition of Si₈₀Ge₂₀. For the certification measurements, we describe the measurement protocols, statistical analysis, the certified Seebeck coefficient values, comprehensive uncertainty budgets, and metrological traceability. Our extensive efforts to identify, reduce, and quantify measurement uncertainties will be emphasized. This new SRM complements SRM 3451 Low-Temperature Seebeck Coefficient Standard (10–390 K) to provide certified reference materials traceable to the International System of Units (SI) for Seebeck coefficient measurements within the temperature range 10–900 K.

Introduction

Background

Thermoelectric effects enable the inter-conversion of thermal and electrical energy, with applications that include solid-state waste heat recovery in engines for automotive and industrial manufacturing; power generation for aerospace, non-terrestrial exploration, and remote sensing; and refrigeration for consumer products, optical components, and microelectronics [1, 2]. Rising economic and environmental pressures demand further improvements to energy conversion technologies. The dimensionless figure of merit, $ZT = S^2 \sigma T / \kappa$, is useful to describe the energy conversion effectiveness of a thermoelectric material, where S is the Seebeck coefficient, σ is the electrical conductivity, T is the absolute temperature, and κ is the total thermal conductivity [1, 2]. Materials that exhibit a large Seebeck coefficient, in addition to high electrical conductivity and low thermal conductivity, are considered candidates for use in thermoelectric applications. The Seebeck coefficient is a widely measured transport property that provides fundamental information on charge carrier transport and the electronic structure of materials, as it can be related to the reduced Fermi level, band gap, carrier concentration, effective mass, and carrier scattering mechanisms [1, 3]. More specifically, the Seebeck coefficient is an important predictor of thermoelectric material performance; it is the proportionality constant that quantifies the energy conversion of an applied temperature difference into an electric potential.

Measurement of the Seebeck coefficient

At high temperatures, the Seebeck coefficient is measured using thermocouples, requiring three voltage measurements: one for the thermoelectric voltage V and one each for the hot and cold thermocouple voltage for T_2 and T_1 , respectively that determine the temperature difference ΔT . The contacts between the probes and the sample must be Ohmic and isothermal. In addition, the thermoelectric voltage and the two temperatures must be measured at the same locations and at the same time.

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The thermoelectric voltage is measured between the two thermocouple beads using either the matched positive or negative wires from each thermocouple. The Seebeck coefficient of these wires must be well characterized over a broad temperature range to properly correct the Seebeck coefficient of the sample. Since thermocouples provide a *relative* measure of temperature, the design of the reference (cold) junction and the connections between the thermocouple wires and the voltmeters are of critical importance [3, 4].

In most commercially available and custom-developed instrumentation, the Seebeck coefficient is measured using the differential method. In this method, a small temperature difference ΔT is applied to the sample at an average temperature of interest $T_0 = (T_1 + T_2)/2$, where $T_1 = T_0 - \Delta T/2$, and $T_2 = T_0 + \Delta T/2$. The Seebeck coefficient is obtained by the ratio of the voltage and the temperature difference: $S = V/\Delta T$, where $V = V^+ - V^-$ is the voltage [3].

The differential method is defined by three thermal conditions: steady state (DC), quasi-steady state (QDC), and transient (AC). Under the steady-state condition, a collection of stabilized electric potential/temperature difference data points $\{(\Delta T, V)\}$ is measured. The Seebeck coefficient is calculated as the slope of the unconstrained linear fit to the data, since the experimental data cannot be assumed to be collinear with the origin (V=0, $\Delta T = 0$). In the guasi-steady-state condition, the temperature difference across the sample is increased as a function of time during which a collection of voltage and temperature differenceordered pairs are simultaneously measured. The use of three nanovoltmeters is recommended under the quasi-steady-state condition: one for the thermoelectric voltage V and one each for the hot and cold thermocouple voltage for T_2 and T_1 . Using only one voltmeter and a voltage channel switcher would introduce error in the measured Seebeck coefficient by staggering the acquisition of the V, T_2 , and T_1 parameters and distorting the temperature-voltage correspondence. In comparison studies, data measured under the steady-state and the quasi-steadystate conditions agree within the measurement uncertainty [4].

Thermal contact errors between the sample and the thermocouple probes are highly sensitive to the probe arrangement [4, 5]. A thermocouple or probe in direct contact with the sample will perturb the temperature of the sample's surface. In the 2-probe arrangement, the electric potential and the temperature difference are measured *on the probes* that are in contact with the ends of the sample. In the 4-probe arrangement, the electric potential and the temperature difference are measured directly *on the sample* at two different locations equally spaced between the hot and cold probes. The 4-probe arrangement is beneficial in instrumentation that consecutively measures the electrical resistivity. Experimental studies and finite element analysis have both demonstrated that these thermal errors are asymmetric for both probe arrangements and are much larger in magnitude for the 4-probe arrangement as compared to those for the 2-probe arrangement [4, 5]. For high accuracy Seebeck coefficient measurements, the 2-probe arrangement is recommended. References 3 and 4 provide an overview of Seebeck metrology at high temperature, including guidelines that enable researchers to develop estimates of measurement uncertainty and thermal contact errors in their own instrumentation.

Round-robin studies and motivation

International research efforts to discover, characterize, and commercialize thermoelectric energy conversion materials and devices have been slowed by the lack of uniform measurement protocols and certified reference materials, resulting in unreliable measurements and conflicting measurement data that can lead to erroneous breakthroughs. Researchers employ a variety of measurement techniques and contact arrangements to measure the Seebeck coefficient, using both custom-built and commercially available instrumentation. A number of international round-robin comparison studies have been conducted to illuminate the interlaboratory variability in thermoelectric measurement data (note: the statistical analyses include sample-to-sample inhomogeneities but do not separately account for instrumentation uncertainties). The National Institute of Standards and Technology (NIST) led a round-robin comparison in part to also determine the feasibility of producing a lowtemperature Seebeck coefficient SRM, the measurement consistency of the materials, and optimal measurement techniques [6]. Measurements were performed by 12 international laboratories between 2 and 390 K in two rounds for two materials: constantan alloy (55 at.% Cu/45 at.% Ni), and n-type Bi₂Te₃ (the Bi₂Te₃ data comprises 34 datasets on 20 different samples from nine laboratories). The interlaboratory standard deviation for the Seebeck coefficient was $\approx \pm 4\%$ for Bi₂Te₃ and for $\approx \pm 8\%$ for constantan throughout the temperature range. A later comparison study among eight laboratories led by Oak Ridge National Laboratory and the International Energy Agency (IEA)-Implementing Agreement on Advanced Materials for Transportation (AMT) extended the temperature range to 323-498 K for both *n*- and *p*-type Bi₂Te₃ materials and included electrical resistivity measurements [7]. The interlaboratory standard deviation was $\approx \pm 6\%$ for the Seebeck coefficient throughout the temperature range. A 2015 round-robin study led by the same group compared the thermoelectric transport properties of n-type Half-Heusler (Hf_{0.50}Ti_{0.25}Zr_{0.25}NiSn_{0.99}Sb_{0.01}) measured by 11 laboratories from 300 to 773 K, and included heat capacity and thermal diffusivity measurements [8]. This is also the only round-robin study that differentiated 2- and 4-probe arrangements. While the standard deviation for the 2- and 4- probe arrangements each is below $\pm 4\%$, the difference between the mean values of each arrangement ranges from 11.3 to 13.6% through the temperature



range (the 4-probe data were consistently larger in magnitude). A separate high-temperature round-robin study in 2015, led by Institut de Chimie et des Matériaux Paris-Est (ICMPE), compared the thermoelectric transport properties of the skutterudite $Co_{0.97}Ni_{0.03}Sb_3$ measured by eight laboratories (for the Seebeck coefficient) from 300 to 700 K [9]. The interlaboratory standard relative error reported for the Seebeck coefficient ranges between $\approx \pm 6$ and $\approx \pm 11\%$ through the temperature range.

By design, round-robin tests generally include only a relatively small, curated collection of measurement laboratories and often exclude aberrant datasets. It is possible that curated round-robin tests demonstrate better agreement and may not be as representative of the broader thermoelectric community. In addition, the instrumentation and/or measurement techniques used therein often lack diversity, with some studies using data primarily measured on identical commercial instrumentation. The thermoelectric community in aggregate has long recognized and discussed discrepancies in measurement data, including the lack of measurement protocols and certified reference materials for use in calibrating instrumentation.

To address these challenges, in 2011 NIST released SRM 3451: Low-Temperature Seebeck Coefficient Standard (10-390 K) [10]. This SRM enabled, for the first time, instrument validation and the reliable comparison of Seebeck coefficient data between laboratories. Seebeck coefficient measurements are commonly divided into the low (< 295 K) or the mid to high (>295 K) temperature ranges due to differences in sample contact methods, sample dimensions, and instrumentation. The nominal dimensions of SRM 3451 (3.5 mm × 2.5 mm × 8.0 mm) were selected to accommodate dimensional limitations of cryostat-based instrumentation while maintaining the gold/nickel multilayer metal plating on each end for solder wettability. To enable instrument validation and interlaboratory data comparison at high temperatures relevant to waste heat recovery, we have now completed the development of complementary SRM 3452, entitled High-Temperature Seebeck Coefficient Standard (295-900 K). SRM 3452 is a bar-shaped artifact of p-type boron-doped polycrystalline silicon-germanium alloy with a nominal composition of Si₈₀Ge₂₀ and nominal dimensions of 2.5 mm \times 2.5 mm \times 14.0 mm that accommodate the longer sample requirements in both custom-built and commercial instrumentation. For the SRM 3452 material, we describe the synthesis, anneal-quench procedure, and structural and physical characterization. For the certification measurements, we describe the custom measurement instrumentation, measurement protocols, statistical analysis, the certified Seebeck coefficient values, comprehensive uncertainty budgets, and metrological traceability. Our extensive efforts to identify, reduce, and quantify measurement uncertainties will be emphasized. Together, SRM 3451 and SRM 3452 provide certified reference materials traceable to the International System of Units for Seebeck coefficient measurements within the temperature range 10–900 K with a broad overlap region (295–390 K). Temperature-dependent electrical resistivity values for SRM 3452 are included in the Supplementary Information (Table S1 and Fig. S1).

The artifact material

Selection

Several materials were initially identified as candidates for SRM 3452: (1) a metal alloy: constantan (nominally Cu 55 at.%-Ni 45 at.%), (2) a single crystal semiconductor: p-type SiGe, and (3) a polycrystalline semiconductor: p-type SiGe. Candidate identification was informed through literature searches and opinions solicited from community experts via distributed questionnaires and panel discussions at several international conferences. Accordingly, requirements were then identified to select the most appropriate material for SRM 3452, including long-term chemical and transport property stability at high temperature after repeated thermal cycles over a broad temperature range; long-term storage stability under ambient conditions; homogeneity in batch production; low production cost; the ability to be shaped into the specified geometry; moderately large absolute Seebeck coefficient values (≈ 40-200 µV/K), moderate to low thermal conductivity (for thermal gradient formation power requirements), and moderate to high electrical conductivity, over a meaningfully broad portion of the high-temperature regime; and minimal environmental concerns (should be environmentally friendly and non-toxic). Based on these requirements and extremely favorable stability in our previous thermocyclic studies [11], p-type boron-doped polycrystalline silicon-germanium was selected as the SRM 3452 material.

Synthesis

The SRM 3452 material comprises p-type boron-doped polycrystalline silicon-germanium, with a nominal composition of Si₈₀Ge₂₀:B_{2.5}. A 50.6 mm diameter, 18.3 mm thick cylindrical ingot was produced using a combination of ball milling and hot pressing (see Fig. S2). The constituent elements were used as received without further purification or alteration. Elemental silicon (99.999%, Alfa Aesar 38,542, granular), germanium (99.999%, Alfa Aesar 10,191, 3 mm-9 mm pieces), and boron (98%, Alfa Aesar 11,337, powder) were combined in stoichiometric quantities and mechanically alloyed under an inert argon atmosphere for 11 h using a Simoloyer high-kinetic rotor ball mill, a stainless steel milling jar, and stainless steel balls [12]. No liner material or additives were used. The resulting powders were hot pressed at 1420 K for 5 min using direct current sintering under a uniaxial pressure of 35 MPa. A cylindrical graphite (semiconductor grade) die with an inner diameter of two inches



(50.8 mm) was used for the hot press. A 0.3 mm-thin graphite foil was used as a liner for easy ejection. No lubricants or other additives were used. The ingot density was 2.93 g/cm^3 , > 99% of the theoretical density, calculated using the dimensional volume of the cut parallelepipeds.

United Lens Company was commissioned to dice the ingot into parallelepipeds using a webbed (a net of parallel wires) slurry abrasive wire saw. The ingot was fixed using natural beeswax. This dicing process produces square angles and parallel, honed matte surfaces (see Fig. S2). The artifact cutting dimensions were 2.550 (\pm 0.050) mm × 2.550 (\pm 0.050) mm × 14.000 (\pm 0.127) mm, with the 14.000 mm dimension aligned parallel to the longitudinal direction of the cylindrical ingot. For the ingot batch, the nominal artifact dimensions are 2.5 mm × 2.5 mm × 14.0 mm.

For batch SRM certification, all artifacts must be prepared and processed under identical conditions. This requirement informed the ingot geometry. However, the production of large (>25 mm) crack-free ingots is a well-known challenge for thermoelectric materials. The presence of isolated radial cracks in the ingot reduced the total number of usable artifacts from the theoretical production estimate. Each cut artifact was thoroughly inspected under a light stereoscope for transverse cracks and/or chips that could arise from either the pressing or the dicing procedures. Defective artifacts were removed from further processing and collected for regrinding/densification as a possible future certified batch. Minor surface imperfections have no influence on the bulk thermoelectric transport properties. The artifacts were cleaned using hot soapy water to remove residual mounting wax, rinsed three times with 18 MQ·cm deionized water, and rinsed three times with ethanol before drying. The artifacts were then stored in an inert nitrogen glovebox prior to the anneal-quench procedure.

Anneal-quench procedure

In both n- (phosphorus-doped) and *p*-type (boron-doped) silicon–germanium alloys, the solid solubilities of the dopants exhibit temperature-dependent retrograde characteristics [13–18]. When the concentration of dopant in the solid solution exceeds the solubility limit at a specific temperature, the dopant can precipitate out of solution. The precipitates likely form as boron and silicon interstitial clusters [19]. The kinetics of precipitation in silicon–germanium alloys are a function of temperature and time and have been described using the diffusion-limited Lifshitz and Slyozov dopant precipitation model [14]. *N*-type dopants precipitate at significantly lower annealing temperatures than *p*-type, since the diffusion coefficient for phosphorus in Ge is larger than that of boron (\approx 100 times at 1000 K) [13], and the activation energy is smaller.

Following the hot press, the ingot was allowed to cool from 1420 K to room temperature. The graphite die that was in contact with the lateral surface of the ingot and the pressing rams that were in contact with the base and the top of the ingot each have different thermal properties and, therefore, transferred heat from the ingot at different rates. These geometric characteristics, coupled with the low thermal conductivity of the Si₈₀Ge₂₀ material (≈ 6 W/mK), enabled dopants to precipitate nonuniformly throughout the as-pressed ingot as it cooled. While highly doped silicon–germanium alloys are inherently 'metastable,' this dopant precipitation is reversible using an anneal–quench procedure [16, 17, 20].

Four as-pressed diced artifacts were selected at random from the batch to determine the optimal temperature and time required to redissolve the dopants into solid solution. The artifacts were sealed in 16 mm diameter quartz ampoules under a 25 kPa argon atmosphere, immersed in a 1275 K furnace for 24 h, then promptly removed and quenched in ice water. The anneal time was increased in comparison to those in the literature [16, 17]. The Seebeck coefficient of each of these artifacts was measured at room temperature pre- and post-anneal-quench for comparison. The standard deviation (one sigma, normal distribution) of the pre-anneal-quench measurements was 10.4%, while the standard deviation postanneal-quench was significantly reduced to 0.8%. Homogeneous redissolution of the dopants into solid solution ensures the homogeneity of the Seebeck coefficient, which is dependent on the carrier concentration. Based on these results, all 70 artifacts were treated using this anneal-quench procedure. Care was taken to quench each artifact at the same rate by arranging them stack free in full longitudinal contact with the quartz tube. To verify the success of the anneal-quench procedure, each artifact was selected from the batch at random, the Seebeck coefficient was measured at room temperature, and then each artifact was returned to the batch at random. The standard deviation (one sigma, normal distribution) of Seebeck coefficients for the batch was $\approx \pm 1.1\%$.

Characterization

The artifact material was characterized for phase identity and purity using powder X-ray diffraction, the instrumentation comprising a computer-controlled Bragg–Brentano Philips diffractometer equipped with a θ -compensation slit (constant area of sample 12 mm × 12 mm, illuminated throughout the 2 θ range), a graphite diffracted beam monochromator, a scintillation counter, and a solid-state amplifier. The diffraction pattern was collected from 8° to 120° 2 θ for a counting of 0.3 s per step using Ni-filtered Cu K_a radiation (40 kV, 40 mA) and a 0.3° divergence slit. The software packages for data collection (DataScan) and data analysis (Jade) were provided by Materials Data, Inc. The



reference X-ray diffraction patterns of the Powder Diffraction File (PDF4+) used for phase identification were developed by the International Centre for Diffraction Data (ICDD).

The representative powder X-ray diffraction pattern for SRM 3452 is shown in Fig. 1 in comparison with the ICDD reference pattern for Si₈₀Ge₂₀ (PDF 04-022-2155). A trace quantity (<<0.1%) of FeSi₂ (PDF 01-085-5114), a residual contamination from the stainless steel balls used in the mechanical alloying process, was also identified. The least-squares cell parameter refinement method (Jade package) with the space group F4-3 m was used to calculate the lattice parameter: a = 5.4650(5) Å.

Four-probe Hall measurements were conducted at 300 K using a nitrogen-jacketed helium PPMS (Quantum Design, Inc.) with the Alternating Current Transport (ACT) option and a custom measurement sequence. A representative artifact was cut (using an abrasive slurry wire saw) into the nominal dimensions $0.5 \text{ mm} \times 2 \text{ mm} \times 8 \text{ mm}$. The Hall resistance, $R_{\rm H}$, was measured as a function of multiple positive and negative magnetic fields (-2.5 T < B < 2.5 T) to mitigate voltage probe misalignment effects and thermal instabilities. $R_{\rm H}$ values for matching \pm B were averaged using multiple zero field measurements. The carrier concentration was calculated using the relation $n = 1/[(R_{\rm H}/B)]$ (et)], where $R_{\rm H}/B$ is the unconstrained-intercept fitted slope for the collection of $R_{\rm H}$ and B values (Fig. S3), n is the carrier concentration, e is the charge per carrier, and t is the artifact thickness. The carrier concentration is 2.0×10^{20} cm⁻³ with a measurement uncertainty of \pm 5% (expanded uncertainty with k = 2).

The Si:Ge ratio can be approximated from the lattice parameter, *a*, after applying a correction for boron, $a = 5.4309 + 0.02x + 0.027x^2 - \beta N_B$, where β is the lattice correction coefficient and N_B is the boron concentration in cm⁻³. Assuming that the substituted boron concentration



Figure 1: Top: the representative powder X-ray diffraction pattern for SRM 3452. The * identify peaks that correspond to the trace quantity (<<0.1%) of FeSi₂. Bottom: the ICDD reference pattern and corresponding (*hkl*) indices for Si₈₀Ge₂₀ (PDF 04-022-2155).

is equal to the active charge carrier concentration and that $\beta = 5.77 \times 10^{-24} \text{ cm}^{-3}$ (the theoretical lattice correction coefficient of B in Si) [21], then the corresponding nominal composition is Si:Ge $\approx 0.8:0.2$. The lattice parameter, carrier concentration, and nominal composition data are supplemental only and are not certified values.

Thermocyclic stability

In *p*-type silicon–germanium alloys, the Seebeck coefficient has been measured as stable under isothermal annealing for 39, 210 h below 875 K ($Si_{75}Ge_{25}$) [15], for 1500 h below 925 K ($Si_{78}Ge_{22}$) [16], and for 100 h at 1000 K ($Si_{63.5}Ge_{36.5}$) [13]. To characterize the thermal stability as a function of repeated hightemperature cycling (thermocycling), the Seebeck coefficient was measured between 300 and 900 K on a randomly selected artifact. The entire measurement procedure was repeated ten times sequentially using the same mounting and contacts (i.e., the artifact was not removed/remounted between cycles). The maximum artifact temperature of 900 K was selected based on legacy isothermal annealing studies [16, 17]. Detailed experimental protocols and statistical analysis for the thermocycling study can be found in Ref. [11].

A mean curve was defined for the complete ten cycle dataset using an all data regression approach. The same parametric model was then applied to the measured data for each individual thermal cycle to compute a set of interpolated curves having a defined set of shared temperatures. The pointwise variance was computed as the mean of the squares of deviations of each curve from the mean curve (smoothed by applying a spline regression) to determine the distribution of the data. The type A uncertainty was obtained as the square root of the variance function. The type B uncertainty component is defined in the Certification Measurements section. The type A and B standard uncertainty components can then be combined using the root-sum-of-thesquares (RSS) method for a total standard uncertainty, u. The total expanded uncertainty band for the Seebeck coefficient thermocyclic measurement curves is then $S_m(T) = \pm ku$ with k = 2 for a 95% confidence band.

Figure 2a plots the Seebeck coefficient as a function of temperature for the complete set of 10 cycles, including the mean curve, the type A expanded uncertainty band (k=2), and the total expanded uncertainty band (k=2). To characterize the stability of this material, the distribution of the data (the type A component) is compared with the type B component. The type A and type B uncertainty components are plotted in Fig. 2b as a function of temperature. Throughout the temperature range, the type B relative uncertainty is $\approx 1.1\%$. The type A uncertainty component is continuous ($\approx 0.7\%$ relative uncertainty) and smaller than the type B component throughout the entire temperature range.





Figure 2: (a) The Seebeck coefficient as a function of temperature for the complete set of ten cycles, including the mean curve, the type A expanded uncertainty band (k=2), and the total expanded uncertainty band (k=2). (b) The type A and type B uncertainty components are plotted as a function of temperature for comparison.

The Seebeck coefficient is interpolated at defined temperatures as a function of the cycle number to characterize the thermocyclic evolution of the Seebeck coefficient (Fig. S4). The Seebeck coefficient data are extremely consistent and well within the type B uncertainty. The cycle-dependent drift in the Seebeck coefficient is then quantified by calculating the slope of the unconstrained linear fit of the data obtained for each temperature. The average drift in the Seebeck coefficient of $\approx -27 \text{ nV/K}$ per cycle for the temperature range is negligible in comparison to the total measurement uncertainty of $\approx 1.6 \,\mu\text{V/K}$ at 300 K. Furthermore, the direction of the drift is in the opposite direction as compared to the trends observed under long-term isothermal annealing, where the absolute Seebeck coefficient increases as a function of both annealing time and temperature. Based on the above analysis, the SRM 3452 material exhibits extremely favorable stability throughout the temperature range.

Certification measurements

Measurement procedure

Seebeck coefficient measurements were conducted in a customdeveloped apparatus [22]. Instrumentation details are available in the Supplementary Information. Six artifacts were selected at random from the 70 unit batch for certification measurements. The Seebeck coefficient was measured at 13 base temperatures in 50 K intervals between 295 and 900 K in the two probe arrangement using the quasi-steady-state condition of the differential method. Together, these 78 Seebeck coefficient

data points comprise 78 reference temperature voltage measurements, 3120 thermoelectric voltage measurements, and 6240 thermocouple voltage measurements (for 9438 distinct voltage measurements in total). Measurements were conducted under vacuum ($< 10^{-4}$ Pa) following a triple purge and backfill cycle (99.999% UHP He). Graphitic interface foil (Graftech International eGraf HT 1210, 0.25 mm ± 5% thick), cut to 3 mm × 3 mm, was inserted between the artifact and each tungsten electrode to enhance the thermal contact interface. The artifact and the two foil inserts were then compressed between the tungsten electrodes using defined current, velocity, and revolutions of the step motor. This ensured that the pressing force applied to each measured artifact was consistent. The thermal interface quality was verified by comparing the Seebeck coefficient measured at atmospheric pressure (S_A) and under vacuum (S_V) , according to $|S_A - S_V| \le 0.5 u_B$, where u_B is the type B measurement uncertainty component (typically << 0.4 µV/K). Current-voltage (IV) sweeps were conducted to verify Ohmic behavior of the tungsten-artifact contact interfaces, where the $R^2 \ge 0.9999$ for the IV least-square fits and the voltage offsets at I = 0 were < 0.5 μ V.

The thermal stability of the base temperature (the temperature of interest at which the artifact was stabilized prior to measurement) was between 10 and 50 mK throughout the 295–900 K temperature range. At each stabilized base temperature, a small thermal flux was applied to the artifact with heating rates between 5 and 50 mK/s. The maximum temperature difference was $\leq 0.01 T_{\rm B}$, where $T_{\rm B}$ is the base temperature. Forty corresponding voltage (*V*) and temperature difference (ΔT) ordered pairs were simultaneously measured using three bus-triggered Keithley 2182A Nanovoltmeters [number of power line cycles (NPLC) = 5; aperture time = 83.3 ms] in 5 s intervals, where $V = V^+ - V^-$, $\Delta T = T_2 - T_1$, $T_2 > T_1$, and V^+ (V^-) was measured at T_2 (T_1) and at the same time (Fig. 3). The thermocouple reference temperature was measured once for each base temperature.

The total average artifact temperature was calculated as the compound average of the 40 $(T_1 + T_2)/2$ individual average temperatures. The Seebeck coefficient was calculated as the slope of the unconstrained linear fit of the collection of voltage and temperature difference-ordered pairs { $(\Delta T, V)$ }, where $R^2 \ge 0.9999$. This avoids the assumption that the experimental data are collinear with the origin $(V=0, \Delta T=0)$ and eliminates extraneous voltage offsets. Representative plots of *V* versus ΔT at 13 defined temperatures (proximate to the collection of base temperatures: see Statistical Analysis section for details) are shown in Fig. 4 and a representative residual plot of the unconstrained linear regression at 300 K is shown in Fig. 5. The stochastic residuals indicate that the response between the two variables is fully approximated by a linear relationship.

The voltage was measured between the negative T_2 and T_1 thermocouple wires (platinum). The measured Seebeck coefficient was subtracted from the absolute Seebeck coefficient of





Figure 3: Graphic representation of the Seebeck coefficient measurement depicting the voltage and temperature measurement locations, the ceramic supports, the tungsten electrodes (the red and blue rectangles), the two thermocouples, the sample heater, and the artifact.



Figure 4: Representative plots of *V* versus ΔT for the 13 defined temperatures. The lines represent the unconstrained linear fit of the collection of voltage and temperature difference-ordered pairs {(ΔT , *V*)} used to calculate the Seebeck coefficient.

the platinum reference wires to obtain the corrected Seebeck coefficient of the artifact, according to $S_{\text{measured}} = S_{\text{Pt}} - S_{\text{artifact}}$. The absolute Seebeck coefficient of platinum was obtained by using an empirical interpolation function [23]:

$$S_{\text{Pt}}(T) = 0.186 \text{T} \left[\exp\left(-\frac{T}{88}\right) - 0.0786 + \frac{0.43}{1 + (T/84.3)^4} \right] - 2.57$$
(1)

where *T* was the average artifact temperature.



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Figure 5: The residual plot of the unconstrained linear regression (solid line in voltage vs. temperature plot) and the temperature residuals that indicate the linear response between the voltage and the temperature difference for a representative artifact at 300 K.



Figure 6: The raw Seebeck coefficient values measured on the six randomly selected artifacts at the 13 defined temperatures in 50 K intervals between 295 and 900 K (labeled 1–6, respectively, for S1, ..., S6). The regression lines were obtained using Eq. 3 and the coefficient values in Table S2.

Statistical model and certified Seebeck coefficient values

Datasets described in the Measurement Procedure section were used to determine the certified Seebeck coefficient values and the measurement uncertainty using the opensource software environment for statistical computing, *R* [24], and the generic function for linear models *lm*(). The raw data are plotted in Fig. 6. A NIST certified value is a value for which NIST has the highest confidence in its accuracy in that all known or suspected sources of bias have been investigated or taken into account [25].

An expanded parametric model was used to fit the measured datasets for curve analysis:

$$S_{\rm m}(T) = S_A + \sum_{i=1}^n a_i (T-A)^i,$$
 (2)



where $S_m(T)$ is the value of the artifact Seebeck coefficient at temperature *T* and *A* is the temperature around which the polynomial is expanded (295 K $\leq A \leq$ 900 K). This form allows physical interpretation for the units of the coefficients: $\mu V/K$ for S_A and $\mu V/K^{i+1}$ for each coefficient a_i , and where *i* is the degree of the corresponding term. *A* was selected to be 295, such that S_A is the Seebeck coefficient value at 295 K. Based on the curvature of the temperature dependence (informed by the physics of the artifact material) and preliminary curve fitting, *n* was set to 2 for a quadratic polynomial, where *a* and *b* are the coefficients for the linear and quadratic terms, respectively:

$$S_{\rm m}(T) = S_A + a(T - 295) + b(T - 295)^2.$$
 (3)

Analysis of covariance (ANCOVA), a hybrid of the analysis of variance model and regression analysis [26, 27], was applied to generate parameter estimates, provide an analysis of variance for the function data, and assess which variant of the model parameters and interaction terms was the most appropriate to describe the measured data. The quadratic polynomial model was then fit to each artifact dataset. The coefficient values for the intercept and linear terms were given directly by the model output (Table S2). Based on the analysis of covariance, the coefficient for the quadratic term was defined as common for the combined dataset. The mean coefficient values (Table S2) were obtained by the mean of each regression coefficient:

> $S_A = 1.16246764 \times 10^2 \mu V/\text{K},$ $a = 2.343158 \times 10^{-1} \mu V/\text{K}^2,$ $b = -8.781594 \times 10^{-5} \mu V/\text{K}^3.$

Since the Seebeck coefficients were measured at marginally dissimilar base temperatures, a set of shared temperatures were defined common to all artifact curves between 295 and 900 K. The certified Seebeck coefficient values were computed at these defined temperatures using the quadratic polynomial model (Eq. 3) and the mean coefficient values (Table S2). The Seebeck coefficient values for each of the six artifact curves were also computed using the individual coefficients, even if not directly observed at the defined temperatures (Table 1). The quadratic polynomial (Eq. 3) and the mean regression coefficients enable the interpolation of Seebeck coefficient values at any temperature between 295 and 900 K. The certified Seebeck coefficient values, the Seebeck coefficient values for each of the six artifact curves, and the mean quadratic polynomial regression are plotted in Fig. S6 as a function of the defined temperature.

Type A uncertainty

Uncertainty analysis was conducted in accordance with the procedures and definitions contained in the Guide to the Expression of Uncertainty in Measurement (GUM) [28] and the NIST Technical Note 1900 [29]. Uncertainties associated with the results of the Seebeck coefficient measurements were categorized as components that can be evaluated by the application of statistical methods to experimental data (Type A) and evaluations that are not derived from repeated observations (Type B). Note: The purpose of the Type A and Type B classification is to indicate the two different ways of evaluating uncertainty components and is for convenience of discussion only; the classification is not meant to indicate that there is any difference in the nature of the components resulting from the two types of evaluation. Both types of evaluation are characterized via fully specified probability distributions. Irrespective of their provenance and of how they are evaluated, uncertainty components are treated and combined uniformly [29].

The type A uncertainty is calculated using the covariance matrix for the fitted model coefficients S_A , a, and b. The covariance matrix comprises two component covariance matrices: M_1 (Table S3), the variance–covariance matrix of the coefficient

 TABLE 1:
 Seebeck coefficient values

 $(\mu V/K)$ for all six artifact curves and
 certified Seebeck coefficient values

 (computed mean) as a function of
 the defined temperature.

Temperature (K)	S1	S2	S3	S4	S5	S6	Mean
295	117.30	117.78	115.30	114.78	116.87	115.46	116.25
350	129.99	130.46	127.76	127.29	129.69	128.02	128.87
400	141.07	141.53	138.62	138.20	140.89	138.98	139.88
450	151.71	152.15	149.05	148.68	151.65	149.50	150.46
500	161.90	162.34	159.03	158.71	161.98	159.59	160.59
550	171.66	172.09	168.58	168.30	171.86	169.23	170.29
600	180.98	181.40	177.69	177.46	181.30	178.43	179.54
650	189.86	190.27	186.36	186.17	190.31	187.20	188.36
700	198.31	198.70	194.59	194.45	198.87	195.53	196.74
750	206.31	206.70	202.38	202.29	207.00	203.41	204.68
800	213.87	214.25	209.74	209.69	214.68	210.86	212.18
850	221.00	221.36	216.65	216.65	221.93	217.87	219.24
900	227.68	228.04	223.12	223.17	228.74	224.44	225.87



parameters from the least-square fit of the quadratic polynomial model; and M_2 (Table S4), the sample covariance matrix from the six sets of coefficient vectors in Table S2 that represent the sample-to-sample variability. The final covariance matrix is the sum $M_F = M_1 + M_2$ (Table S5). The variance of the fitted quadratic model prediction values is then given by

$$\operatorname{var}[S_{\mathrm{m}}(T)] = \begin{bmatrix} 1 & (T - 295) & (T - 295)^2 \end{bmatrix} M_{\mathrm{F}} \begin{bmatrix} 1 \\ (T - 295) \\ (T - 295)^2 \end{bmatrix}.$$
(4)

The type A standard uncertainty components, u_A , for the certified Seebeck coefficients values (Table S6), are obtained as the square root of the variance function var $[S_m(T)]$:

$$u_A = \sqrt{\operatorname{var}[S_{\mathrm{m}}(T)]}.$$
(5)

Type B uncertainty

Type B uncertainty evaluations involve the elicitation of expert knowledge (from a single expert or from a group of experts, also from authoritative sources that include calibration certificates and technical publications) and its distillation into probability distributions that describe states of knowledge about the true values of the inputs [29]. The primary type B standard uncertainty sources include the thermocouple (TC) accuracy, the measurement of the T_1 and T_2 thermocouple voltages that determine the temperature difference, the interpolation of the platinum wire Seebeck coefficient correction, the reference temperature to reference voltage conversion, the two thermocouple voltage to temperature conversions, the calibrated platinum resistor reference temperature accuracy, and the thermoelectric voltage measurement. All uncertainty values must be converted into standard uncertainty components prior to being combined using root-sum-of-the-squares (RSS) by dividing by their probability distribution divisor and multiplying by their sensitivity coefficient [28]. The sensitivity coefficient enables the combination of individual uncertainty values having different units of measure or functional relationships. For utility, the sensitivity coefficients are simplified as functions of the parameterized consensus mean to enable the expression and propagation of the uncertainty values in percent. This format further enables the rapid calculation of uncertainty components at different temperatures. The unit of °C is used instead of K to obtain the percent uncertainty when the authoritative source information is provided in °C. Unless otherwise stated, the uncertainty values have negligible temperature dependence and are, therefore, fixed for all temperatures. 300 K was chosen to best represent the most reasonable contribution of type B uncertainty values and to avoid the polarity inversion of the type R thermocouple voltage when the temperature of the thermocouple and the reference junction are identical. All calculations are shown extended to the thousandth place until the expression of the total combined type B uncertainty component.

Since the Seebeck coefficient is calculated as the slope of the unconstrained linear fit of the collection of corresponding voltage and temperature difference-ordered pairs $\{(\Delta T, V)\}$, and R^2 is robust (≥ 0.9999), the uncertainty value of the thermoelectric voltage measurement can be obtained using the mean Seebeck coefficient at 300 K (117.42 μ V/K) and the largest ΔT (1.72 K). Accordingly, the thermoelectric voltage is calculated as $(117.42 \ \mu\text{V/K}) \times 1.72 \ \text{K} = 202 \ \mu\text{V}$. The manufacturer's stated uncertainty for the Keithley 2182A Nanovoltmeter at one year post-calibration is \pm (50 ppm of the voltage reading + 4 ppm of the voltage range), representing the combination of the gain and the offset error terms, respectively (for calibration certificates, see Figs. S7-S9). The uncertainty for the thermoelectric voltage measurement in the 10 mV range is calculated as $[(50 \times 2.02)]$ $\times 10^{-4} \text{ V} + (4 \times 10 \times 10^{-3} \text{ V}) / (1 \times 10^{6} = 50.1 \text{ nV})$, with an uncertainty value of $(50.1 \times 10^{-9} \text{ V})/(2.02 \times 10^{-4} \text{ V}) \times 100 = 0.025\%$. The standard uncertainty component is then obtained by dividing the uncertainty value by $\sqrt{3}$ (since the manufacturer's stated uncertainty is expanded by a rectangular probability distribution) and multiplying by the sensitivity coefficient. The standard uncertainty component for the Seebeck coefficient at 300 K is 0.017 µV/K (Table 2).

Thermocouple manufacturers conform to the ASTM International specifications for calibration accuracy [30]. Accordingly, the manufacturer's stated accuracy represents a definitive uncertainty (99.73%; 3σ divisor). The stated accuracy of the *special limits of error* type R thermocouple wire is ± 0.6 °C or ± 0.1% of reading in °C, whichever is greater. The uncertainty value at 300 K (26.85 °C) is 0.6 °C/26.85 °C × 100 = 2.235%. The standard uncertainty component for the Seebeck coefficient at 300 K is 0.875 µV/K (Table 2).

For a type R thermocouple at 300 K with a reference junction temperature of 298 K, the voltage measured for a type R thermocouple is 11.96 µV. The measured thermocouple voltage scales with the reference junction temperature. The manufacturer's stated uncertainty for the Keithley 2182A Nanovoltmeter at 1 year post-calibration is \pm (50 ppm of the voltage reading + 4 ppm of the voltage range). The uncertainty for the thermocouple voltage measurement in the 10 mV range is calculated as $[(50 \times 11.93 \times 10^{-6} \text{ V}) + (4 \times 10 \times 10^{-3} \text{ V})]/1 \times 1$ $0^{6} = 40.6 \text{ nV}$, with an uncertainty value of $(40.6 \times 10^{-9} \text{ V})/(11$ $.93 \times 10^{-6}$ V) $\times 100 = 0.340\%$. The standard uncertainty component associated with the thermocouple voltage measurement is then obtained by dividing the uncertainty value by $\sqrt{3}$ and multiplying by the sensitivity coefficient. The standard uncertainty component is 0.230 µV/K at 300 K (Table 2). Note: although the thermocouple voltage increases with increasing temperature, the standard uncertainty component is fixed for



TABLE 2: Type B sources of uncertainty and their corresponding percent uncertainty value, probability distribution type and divisor, sensitivity coefficient, and standard uncertainty component at 300 K.

Uncertainty component source	Value (%)	Probability distribution	Divisor	Sensitivity coefficient	Standard uncertainty (µV/K)
Thermoelectric voltage measurement	0.025	Rectangular	√3	S _m (7)	0.017
TC accuracy	2.235	Gaussian	3	<i>S</i> _m (<i>T</i>)	0.875
TC voltage measurement	0.340	Rectangular	√3	<i>S</i> _m (<i>T</i>)	0.230
TC reference temperature to voltage conversion	0.062	Gaussian	1	S _m (<i>T</i>)	0.073
TC voltage to temperature conversion	0.028	Gaussian	1	S _m (<i>T</i>)	0.033
TC reference temperature measurement	0.007	Gaussian	2	S _m (<i>T</i>)	0.004
Total TC temperature measurement component (RSS)	0.773	Gaussian	1	$S_{\rm m}(T)$	0.908
Seebeck coefficient LS regression	1.093	Gaussian	1	<i>S</i> _m (<i>T</i>)	1.283
Average artifact temperature	0.547	Gaussian	1	<i>T</i> [<i>S</i> ′ _m (<i>T</i>)]	0.383
Interpolation of Pt Seebeck coefficient correction	0.085	Gaussian	1	<i>S</i> _m (300)	0.100
Combined type B component (RSS)					1.34

all temperatures to best represent the most reasonable contribution of this uncertainty component.

The thermocouple reference temperature was measured using a calibrated platinum resistor. A 0.5 mA current was sourced through the platinum resistor using a NI PXI-4110 DC power supply, and the corresponding voltage was measured using a Keithley 2182A Nanovoltmeter. The temperature is obtained using the measured resistance value and the Chebychev polynomial for the 260-500 K range in the calibration report (see Fig. S10). The RMS error of fit is 2.65 mK. The total uncertainty at 298 K (the typical room temperature value of the instrumentation), which includes the uncertainty of the resistance measurement, is 22 mK. The uncertainty value associated with the reference temperature is given by 0.022 K/298 K \times 100 = 0.007%. The standard uncertainty component associated with the reference temperature measurement is then obtained by dividing the uncertainty value by 2 (since the uncertainty stated in the calibration report is expanded by a normal probability distribution with a coverage factor k = 2) and multiplying by the sensitivity coefficient. The standard uncertainty component is 0.004 µV/K at 300 K.

The thermocouple reference temperature was then converted into a thermocouple reference voltage using the coefficients for the ninth degree polynomial reference function that gives the thermoelectric voltage of type R thermocouples as a function of temperature in the – 50 °C to 1064.18 °C range [31]. The residual of this fit is 0.087 μ V. The uncertainty value for a reference junction at 298 K (where the calculated thermocouple reference voltage is 139.7 μ V) is then 0.087 μ V/139.7 μ V × 100 = 0.062%, with a standard uncertainty component of 0.073 μ V/K at 300 K (Table 2). The reference voltage is added to the measured thermocouple voltage and

the thermocouple temperature is then calculated using the approximate inverse reference functions. The error that represents the maximum difference between temperature values calculated from the approximate inverse function and those obtained from the reference function for type R thermocouples is 0.0075 °C for all temperatures measured in °C. The uncertainty value is given by 0.0075 °C/*T* (°C), or 0.0075 °C/26.85 °C × 100 = 0.028% for a standard uncertainty component of 0.033 μ V/K at 300 K.

The uncertainty values for the thermocouple accuracy, the measurement of the thermocouple voltage, the platinum resistor reference temperature accuracy, the reference temperature to reference voltage conversion, and the thermocouple voltage to temperature conversion were by divided by their probability distribution divisor, multiplied by their sensitivity coefficient, and then combined using the RSS method to obtain the total thermocouple temperature measurement standard uncertainty component. The combined uncertainty value is 0.773% and the standard uncertainty component for the thermocouple temperature measurement for the thermocouple temperature measurement is 0.908 μ V/K at 300 K. The uncertainty value for ΔT can be computed by (0.773² + 0.773²)^{1/2}% = 1.093%.

Since the Seebeck coefficient is calculated as the slope of the unconstrained linear fit of the collection of corresponding voltage and temperature difference-ordered pairs { $(\Delta T, V)$ }, where $R^2 \ge 0.9999$, the standard uncertainty component for the Seebeck coefficient least-squares (LS) regression is computed using the uncertainty values for the thermocouple temperature measurements and the thermoelectric voltage measurement. These uncertainty values are by divided by their probability distribution divisor, multiplied by their sensitivity coefficient, and then combined using the RSS method to obtain the standard uncertainty component for the Seebeck coefficient LS regression.



The uncertainty value is $[2(0.773)^2 + (0.025/\sqrt{3})^2]^{1/2}\% = 1.093\%$, and the standard uncertainty component is 1.283 µV/K at 300 K.

The total average artifact temperature is calculated as the compound average of the 40 $(T_1 + T_2)/2$ individual average temperatures. Therefore, the uncertainty value for the average temperature can be obtained in terms of the uncertainties for individual thermocouple temperature measurements: $[(0.773/2)^2 + (0.773/2)^2]^{1/2}\% = 0.547\%$. The Seebeck coefficient standard uncertainty component associated with this average temperature uncertainty value is then calculated through multiplication by the sensitivity coefficient: $(0.00547)T[S'_m(T)]$, where $S'_m(T)$ is the derivative of the mean quadratic polynomial regression.

To calculate the corrected Seebeck coefficient of the artifact, according to: $S_{\text{measured}} = S_{\text{Pt}} - S_{\text{artifact}}$, the absolute Seebeck coefficient of platinum is obtained using an empirical interpolation function [23]. The uncertainty value for all average artifact temperatures is 0.1 μ V/K. The uncertainty value at 300 K is 0.085%, where the standard uncertainty component is obtained through multiplication by the sensitivity coefficient S_m(300) (Table 2).

Finally, the standard uncertainty component for the Seebeck coefficient LS regression, the average artifact temperature, and the interpolation of the Pt Seebeck coefficient correction, are combined using the RSS method to obtain the total combined type B uncertainty component, $u_{\rm B}$: 1.34 µV/K at 300 K (Table 2). The combined type B uncertainty component is calculated for the certified Seebeck coefficient value at each defined temperature using the analysis described in this section (Table 3).

Total expanded uncertainty

The type A and type B standard uncertainty components are combined using the RSS method for a total uncertainty, u_c . The total expanded uncertainty for the certified Seebeck coefficient values is $\pm ku_c$ with a normal distribution coverage



Figure 7: The certified Seebeck coefficient values, the individual Seebeck coefficient values for each of the six artifact curves, the mean quadratic polynomial regression, and the expanded uncertainty intervals.

Temperature (K)

factor k = 2 for an approximately 95.45% coverage probability (Table 3). Figure 7 plots the certified Seebeck coefficient values, the individual Seebeck coefficient values for each of the six artifact curves, the mean quadratic polynomial regression, and the expanded uncertainty intervals. The uncertainty for any Seebeck coefficient value interpolated between the discrete certification temperatures (obtained using Eq. 3 and the mean coefficient values), is given approximately by the uncertainty value at a proximate certified temperature value in Table 3. The relative expanded uncertainty $[2u_c/S_m(T)]$ is $\approx \pm 3\%$ for all temperatures. The relative type A uncertainty ($\approx 1.1\%$) is identical to the standard deviation (one sigma, normal distribution) of the Seebeck coefficients obtained from the anneal-quench verification measurements on the entire batch. This indicates that the randomly sampled batch certification method provides a reasonable representation of

TABLE 3: Certified Seebeck coefficient values, type A and type B uncertainty components, the total uncertainty, and the expanded uncertainty (k=2) as a function of defined temperature.

Temperature (K)	Certified val- ues (µV/K)	Type A uncer- tainty (µV/K)	Type B uncer- tainty (μV/K)	Total uncer- tainty (μV/K)	Expanded uncertainty (µV/K)
295	116.25	1.24	1.33	1.82	3.63
350	128.87	1.34	1.48	1.99	3.99
400	139.88	1.44	1.60	2.16	4.31
450	150.46	1.55	1.72	2.32	4.63
500	160.59	1.66	1.84	2.48	4.95
550	170.29	1.77	1.95	2.63	5.26
600	179.54	1.88	2.05	2.78	5.57
650	188.36	1.99	2.15	2.93	5.86
700	196.74	2.11	2.24	3.08	6.15
750	204.68	2.22	2.33	3.22	6.44
800	212.18	2.34	2.41	3.36	6.72
850	219.24	2.46	2.48	3.49	6.99
900	225.87	2.58	2.55	3.63	7.26



the full batch of artifacts, and that the statistical model and uncertainty analysis provide a reasonable assessment of the artifact variation. Instructions for handling, use, and storage of SRM 3452 are provided in the Certificate of Analysis [32].

Metrological traceability

The 78 measured Seebeck coefficient data points comprise 78 reference temperature voltage measurements, 3120 thermoelectric voltage measurements, and 6240 thermocouple voltage measurements (one each for the hot and cold thermocouple voltage for T_2 and T_1 , respectively that determine the temperature difference ΔT), for 9438 unique voltage measurements in total. Prior to certification measurements, all three Keithley 2182A Nanovoltmeters were calibrated by Keithley (a Tektronix Company) using measurement standards traceable to the International System of Units (SI) through NIST and meets the requirements of the International Organization for Standardization/International Electrotechnical Commission (ISO/ IEC) 17,025:2005 and American National Standard Institute/ National Conference of Standards Laboratories (ANSI/NCSL) Z540.3-2006. The quality system is registered to ISO 9001. The SRM 3452 certification measurements were conducted within 8 months post-calibration, such that the Type B uncertainty components were obtained using the 1-year post-calibration accuracy values in the manufacturer's published specifications. Calibration certificates are available in the Supplementary Information (Figs. S7-S9).

The reference temperature was measured using a calibrated platinum resistor (Lake Shore Cryotronics, Inc. Model PT-103-AM-70H). The calibration certificate is available in the Supplementary Information (Fig. S10). The platinum resistor was calibrated in the temperature range 70.0-500 K. This temperature sensor has been calibrated to the International Temperature Scale of 1990 (ITS-90) or the Provisional Low-Temperature Scale (PLTS-2000) as appropriate. The calibrations are traceable to the National Institute of Standards and Technology, the National Physical Laboratory (NPL, United Kingdom), the Physikalisch-Technische Bundesanstalt (PTB, Germany), or natural physical constants. Lake Shore Cryotronics, Inc. maintains ITS-90 and PLTS-2000 on standard platinum (PRT), rhodiumiron (RIRT), and germanium (GRT) resistance thermometers that have been calibrated directly by an internationally recognized national metrology institute (NIST, NPL, PTB) for T < 330 K or an ISO 17,025 accredited metrology laboratory for 330 K < T < 800 K. These standards are routinely intercompared to verify consistency and accuracy of the temperature scale. The sensor calibrations are performed by comparison to laboratory standard resistance thermometers and tested in accordance with Lake Shore Cryotronics, Inc. Quality Assurance Manual. The quality system of Lake Shore Cryotronics Inc. is registered to ISO 9001.

Conclusions

We have successfully developed a new high-temperature (295–900 K) Seebeck coefficient Standard Reference Material. SRM 3452 will enable instrument validation and interlaboratory data comparison that support international research efforts to discover, characterize, and commercialize thermoelectric materials and devices at high temperatures relevant to waste heat recovery. Together with SRM 3451 Low-Temperature Seebeck Coefficient Standard (10–390 K), these two SRMs now provide SI traceable certified reference materials for Seebeck coefficient measurements within the temperature range 10–900 K with a broad overlap region (295–390 K).

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Data availability

The authors confirm that the data supporting the key findings can be made available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare that there are no conflict of interest.

Supplementary Information

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