

A SYSTEM AND A METHOD OF PERFORMING AUTOMATED SCREENING OF THERMOELECTRIC MATERIALS

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TECHNICAL FIELD

The present disclosure relates broadly to a system and a method of performing automated screening of thermoelectric materials.

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BACKGROUND

In general, characterization of thermoelectric properties of a material are typically performed by applying a differential temperature profile to a known form factor and subsequently measuring the potential difference between two points of known physical separation. Commercial equipment isolates the material environment to prevent heat loss, resulting in long measurement times (hours to days) because they are unable to model the thermal profile at each section of the material, instead using thermocouples to measure the temperature only at the ends.

The performance of a thermoelectric material is typically evaluated using the figure of merit (ZT), which is a dimensionless quantity. The figure of merit encapsulates the efficiency of a thermoelectric material to convert heat into electricity (or vice versa) and is defined as:

$ZT = \frac{S^2 \sigma T}{\kappa}$, where S is the Seebeck coefficient, σ is the electrical conductivity, κ is thermal conductivity and T is the temperature. The components of ZT describe the thermoelectric material's ability to balance electrical and thermal properties for maximum energy conversion efficiency.

The process of measuring the Seebeck coefficient is inherently intricate and time-consuming, posing significant challenges for the rapid development and discovery of thermoelectric materials. Accurate measurement requires precise control of temperature gradients, stable thermal environments, and sensitive detection of the resulting voltage

differences. These requirements necessitate meticulous calibration of experimental setups and careful handling of samples, making the process labor-intensive.

For materials discovery, the traditional approach involves running detailed and
5 complex measurements on hundreds or even thousands of candidate samples. This paradigm
is incompatible with the urgency to accelerate the transition of novel materials from discovery
to real-world applications. Each measurement can take hours to days, depending on the
material's properties and the range of temperatures being tested. Such prolonged timelines
hinder the exploration of large compositional spaces and limit the ability to identify promising
10 candidates efficiently.

The need for high-throughput measurements has become increasingly apparent. High-
throughput systems can simultaneously evaluate multiple samples, significantly reducing the
time required to gather data. However, these systems often require sophisticated equipment,
15 advanced automation, and algorithms to ensure accuracy and consistency across a large
dataset. Even with these advancements, challenges such as variability in sample preparation,
alignment issues, and potential measurement artifacts persist, further complicating the task.

Thus, there is a need for a system and a method of performing automated screening
20 of thermoelectric materials that seek to address or alleviate at least one of the above problems.

SUMMARY

25 In accordance with a first aspect of the present disclosure, there is provided a system
for performing automated screening of thermoelectric materials, the system comprising, a
temperature control stage for introducing a temperature gradient, said temperature control
stage comprising a thermally conductive sheet dimensioned to support a wafer having a
diameter of at least 4 inches and a plurality of samples disposed on a surface thereof; a
30 thermal camera for measuring a temperature profile along the wafer and a temperature
gradient across each sample disposed on the wafer; an electrical probe for performing
electrical measurements on the plurality of samples; and a processing unit for determining one
or more thermoelectric properties of the plurality of samples based on the electrical
measurements; wherein the electrical probe is configured to move, in response to instructions
35 from a vision algorithm, to target locations associated with the plurality of samples.

In the system of the present disclosure, the temperature control stage may further comprise, a Peltier module coupled to one end of the thermally conductive sheet for providing localized heating; and a heat sink coupled to an opposite end of the thermally conductive sheet
5 for maintaining the opposite end of the thermally conductive sheet at room temperature.

In the system of the present disclosure, the temperature control stage may further comprise a heater controller system coupled to the Peltier module, said heater controller system configured to control a flow of current to the Peltier module.
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In the system of the present disclosure, the processing unit may be configured to control the heater controller system using a pulse-width modulation (PWM) signal generated by a proportional-integral-derivative (PID) algorithm.

In the system of the present disclosure, the system may further comprise a probe deployment actuator coupled to the electrical probe, wherein the probe deployment actuator is configured to move the electrical probe along three axes of translation to the target locations associated with the plurality of samples.
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In the system of the present disclosure, the system may further comprise a source measure unit coupled to the electrical probe for performing the electrical measurements, wherein the electrical measurements comprise a sheet resistance of each sample when subjected to the temperature gradient, and an open circuit voltage of each sample when subjected to the temperature gradient.
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In the system of the present disclosure, the electrical probe may comprise four probes arranged linearly along a straight line and spaced equidistant from each other; two of the probes may be configured to measure the open circuit voltage for each sample at multiple temperature gradients; and the four probes may be configured to measure the electrical
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30 resistance of each sample.

In the system of the present disclosure, the thermal camera may be further configured to provide a thermal feed as input to the vision algorithm for instructing the electrical probe to the target locations.
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In the system of the present disclosure, the thermally conductive sheet may have a thickness that is tuned to one or more thermal properties of the plurality of samples.

5 In the system of the present disclosure, the one or more thermoelectric properties may comprise an electrical conductivity of each sample, and a Seebeck coefficient of each sample.

10 In accordance with a second aspect of the present disclosure, there is provided a method of performing automated screening of thermoelectric materials, the method comprising, providing a wafer having a diameter of at least 4 inches and a plurality of samples disposed on a surface thereof; positioning the wafer on a thermally conductive sheet of a temperature control stage and introducing a temperature gradient; measuring a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer using a thermal camera; performing electrical measurements using an electrical probe on the plurality of samples; moving the electrical probe, in response to instructions from a vision algorithm, to target locations associated with the plurality of samples; and determining one or more thermoelectric properties of the plurality of samples based on the electrical measurements using a processing unit.

20 In the method of the present disclosure, the method may further comprise, heating one end of the thermally conductive sheet using a Peltier module coupled thereto; and maintaining an opposite end of the thermally conductive sheet at room temperature using a heat sink coupled thereto.

25 In the method of the present disclosure, the method may further comprise controlling a flow of current to the Peltier module using a heater controller system coupled thereto.

30 In the method of the present disclosure, the method may further comprise controlling the heater controller system using a pulse-width modulation (PWM) signal generated by a proportional-integral-derivative (PID) algorithm.

In the method of the present disclosure, the method may further comprise moving the electrical probe along three axes of translation to the target locations associated with the plurality of samples using a probe deployment actuator coupled to the electrical probe.

In the method of the present disclosure, the method may further comprise performing the electrical measurements using a source measure unit coupled to the electrical probe, wherein the electrical measurement is a sheet resistance of each sample when subjected to the temperature gradient, and an open circuit voltage of each sample when subjected to the temperature gradient

In the method of the present disclosure, the step of measuring electrical and thermoelectric measurements may comprise, measuring the open circuit voltage for each sample at multiple temperature gradients using two probes of a four-point probe having four probes arranged linearly along a straight line and spaced equidistant from each other; and measuring the electrical resistance of each sample using all four probes of the four-point probe

In the method of the present disclosure, the method may further comprise providing a thermal feed using the thermal camera as input to the vision algorithm for instructing the electrical probe to the target locations.

In the method of the present disclosure, the thermally conductive sheet may have a thickness that is tuned to one or more thermal properties of the plurality of samples.

In accordance with a third aspect of the present disclosure, there is provided a non-transitory computer readable storage medium having stored thereon instructions for instructing a method of performing automated screening of thermoelectric materials, the method comprising, providing a wafer having a diameter of at least 4 inches and a plurality of samples disposed on a surface thereof; positioning the wafer on a thermally conductive sheet of a temperature control stage for introducing a temperature gradient; measuring a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer using a thermal camera; performing electrical measurements using an electrical probe on the plurality of samples; moving the electrical probe, in response to instructions from a vision algorithm, to target locations associated with the plurality of samples; and determining one or more thermoelectric properties of the plurality of samples based on the electrical measurements using a processing unit.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 is a schematic diagram of a system for performing automated screening of thermoelectric materials in an example embodiment.

FIG. 2 is a schematic diagram of a stage / temperature control stage / temperature gradient heating stage in an example embodiment.

FIG. 3 is a schematic diagram showing a perspective view of a system for performing automated screening of thermoelectric materials in an example embodiment.

FIG. 4 is a schematic flowchart illustrating a method of performing automated screening of thermoelectric materials in an example embodiment.

FIG. 5 is a photograph of a system for performing automated screening of thermoelectric materials in an example embodiment.

FIG. 6 is a thermal image of a plane view of a wafer having a plurality of samples disposed on a surface thereof in an example embodiment.

FIG. 7 is a thermal gradient map of a wafer from an ANSYS simulation in an example embodiment.

FIG. 8 is a graph illustrating a linearly fitted line and an exponentially fitted line, generated using an interpolation method to estimate temperatures at surface locations of a sample in an example embodiment.

FIG. 9 is a graph comparing actual surface temperatures measured along a surface of a 4-inch wafer with surface temperatures predicted by a simulation in an example embodiment.

FIG. 10 is a thermal image of a wafer positioned on a temperature control stage in an example embodiment.

FIG. 11 is a composite illustration of two vertically arranged graphs, with the top graph showing raw open circuit voltages measured from a sample over a time period, and the bottom graph showing temperatures gradient of the sample over the same time period in an example embodiment.

FIG. 12 is a graph illustrating variation of a sample's open-circuit voltage with temperature difference and demonstrating how a steady-state Seebeck coefficient is determined from a slope of the graph in an example embodiment.

FIG. 13 is a graph illustrating variation of a sample's electrical conductivity with heater temperature in an example embodiment.

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FIG. 14 is a graph showing a test of measurement repeatability by comparing Seebeck coefficients measured by the presently disclosed system with that measured by commercial equipment across different run numbers in an example embodiment.

FIG. 15 is a schematic drawing of a computer system suitable for implementing an example embodiment.

DETAILED DESCRIPTION

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Example, non-limiting embodiments may provide a system and a method of performing automated screening of thermoelectric materials.

In various embodiments, the term "thermoelectric property" as used herein broadly describes a material's ability to convert heat into electricity (Seebeck effect) or electricity into heat (Peltier effect). Examples of thermoelectric properties include Seebeck coefficient, electrical conductivity, thermal conductivity, power factor, and figure of merit ZT .

In various embodiments, the term "electrical property" as used herein broadly describes the ability of a material to conduct electric current. It will be appreciated that an

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electrical property is not unique to thermoelectric materials but may influence a thermoelectric material's role in conducting electricity. Examples of electrical properties include electrical conductivity and electrical resistivity.

5 FIG. 1 is a schematic diagram of a system 100 for performing automated screening of thermoelectric materials in an example embodiment. The system 100 comprises a stage / temperature control stage 102 for introducing a thermal / temperature gradient, said temperature control stage 102 comprising a thermally conductive sheet 104 dimensioned to support a wafer 106 having a diameter of at least 4 inches and a plurality of samples, e.g.,
10 108, disposed on a surface thereof. The system 100 further comprises a thermal camera 110 for measuring a temperature profile along the wafer 106 and a temperature gradient across each sample 108 disposed on the wafer 106. The system 100 further comprises an electrical probe 112 for performing electrical measurements on the plurality of samples, e.g., 108 (e.g., when subjected to the temperature gradient). The system 100 further comprises a processing
15 unit 114 for determining one or more thermoelectric properties of the plurality of samples, e.g., 108, based on the electrical measurements. In the example embodiment, the electrical probe 112 is configured to move, in response to instructions from a vision / computer vision algorithm, to target locations associated with the plurality of samples, e.g., 108.

20 In the example embodiment, the system 100 is built in a modular fashion, advantageously allowing for custom workflows to be developed to study the thermoelectric behavior of materials. The system 100 advantageously integrates three modular components, i.e., temperature imaging, computer vision, and thermoelectric transport characterization together to perform fast and accurate measurement of the thermoelectric and electrical
25 properties, e.g., Seebeck coefficient and electrical conductivity, of thin-film thermoelectric materials. The system 100 may advantageously allow automated high-throughput screening of thermoelectric materials.

 In the example embodiment, the temperature control stage 102 provides controlled
30 temperature gradients for accurate determination of thermoelectric and electrical properties. The thermally conductive sheet 104 is specifically dimensioned to support the wafer 106 with a minimum diameter of 4 inches (or about 100 mm). The thermally conductive sheet 104 is also specifically dimensioned to maintain controlled temperature gradients across the entire wafer 106. The inventors have recognized that the use of a thermally conductive material
35 would typically generate a relatively small thermal gradient, resulting in a potential difference

that is too small to be measurable. In the example embodiment, the thermally conductive sheet 104 may be dimensioned such that its thickness is tuned / adjusted to, or based on one or more thermal properties of the sample 108. Examples of such thermal properties may include thermal conductivity, heat capacity, and thermal resistance. For example, the thermally conductive sheet 104 may have a thickness which is specifically optimized based on finite element analysis (FEA) modeling of the wafer 106. This may advantageously facilitate the generation of a relatively large thermal gradient across the wafer/sheet composite, taking into account thermal transfer rate and loss to radiation and convection. The thermally conductive sheet 104 may have a thickness falling in the range of from about 0.4 mm to about 1 mm. The thickness of the thermally conductive sheet 104 may fall in the range with start and end points selected from the following group of numbers: 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1 mm. In general, a thicker thermally conductive sheet 104 reduces the temperature gradient. The thermally conductive sheet 104 may measure about 16 cm (length) by 10 cm (width) for a 4-inch wafer. The length and width dimensions of the thermally conductive sheet 104 may increase in this proportion to accommodate wafers with larger diameters. The thermally conductive sheet 104 may be made of metal, i.e., a metal sheet. Suitable metals for making the thermally conductive sheet 104 include but are not limited to aluminum, copper, silver, gold, and iron.

In the example embodiment, the thermal camera 110 is configured for measuring a temperature profile along the wafer 106 and a temperature gradient across each sample 108 disposed on the wafer 106. The thermal camera 110 is capable of performing thermal imaging on the sample to determine a temperature at each point of the image captured by the thermal camera 110. The thermal camera 110 may be positioned relative to the temperature control stage 102 such that the wafer 106 with the plurality of samples, e.g., 108, can be detected. The thermal camera 110 may be positioned to obtain in-plane temperature measurements (e.g., temperature gradients along a surface of the sample 108). For example, the thermal camera 110 may be positioned above the temperature control stage 102 to capture a top-down view of the wafer 106 with the plurality of samples, e.g., 108. The thermal camera 110 may be positioned substantially perpendicularly to the plane surface of the wafer 106, such that its optical axis is aligned normal to the plane surface of the wafer 106. The thermal camera 110 offers a unique solution to the problem of fast and accurate measurements. The thermal camera 110 may advantageously provide fast, accurate, non-contact and high-throughput temperature measurements for visual inspection of the thermal gradient, as compared to conventional systems that use a thermocouple probe for temperature measurement.

In the example embodiment, the thermal camera 110 is further configured to provide a visual/thermal feed as input to the vision algorithm for instructing the electrical probe 112 to the target locations associated with the plurality of samples, e.g., 108, on the surface of the wafer 106. A target location associated with the sample 108 refers to the position of the sample
5 108 on the wafer 106 and may also include any specific part of the sample 108. The thermal feed of the thermal camera 110 refers to the real-time image or video generated by the thermal camera 110 based on infrared radiation emitted by objects. The thermal feed provides a visual representation of temperature variations across a surface, allowing users to see thermal patterns and detect heat-related features that are invisible to the naked eye. In other words,
10 the thermal camera 110 may advantageously provide dual benefit of temperature metrology as well as a visual feed for the vision algorithm / image processing algorithm that guides the electrical probe 112. Therefore, there is an advantageous synergy between the technologies of radiometric thermometry and automated probe manipulation with machine vision for automated measurements.

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In the example embodiment, the electrical probe 112 is configured for performing electrical and Seebeck measurements on the plurality of samples, e.g., 108. The electrical probe 112 is guided by machine vision combining thermal and optical feed to detect sample positions and perform automated measurements. Examples of electrical measurements that
20 can be measured using the electrical probe 112 include electrical resistance e.g., sheet resistance across the sample 108, and an open circuit voltage / potential across the sample 108 caused by / when subjected to the temperature gradient.

In the example embodiment, the processing unit 114 functions as a central computer
25 for coordinating the various components of the system 100. The processing unit 114 is communicatively coupled to the temperature control stage 102, thermal camera 110, and the electrical probe 112. The term "communicatively coupled" as used herein is intended to mean coupling of components in a way to permit communication of information therebetween. That is, components are capable of transmitting data signals with one another such as for example,
30 electrical signals via a conductive medium, electromagnetic signals via air, optical signals via optical waveguides, and the like. The term "communicatively coupled" as used herein is also intended to mean either a direct or an indirect communication connection. For example, the temperature control stage 102, thermal camera 110, and electrical probe 112 may be communicatively coupled to the processing unit 114 by means of wired electrical connection,
35 wireless network connection, or a mixture thereof.

In the example embodiment, the wafer 106 may be circular in shape. It will be appreciated that the wafer 106 may have other shapes such as a square, rectangle, semicircle or quadrant. The wafer 106 may have a diameter falling in the range of from about 4 inches to about 11.8 inches (usually referred to as "12 inches", or about 300 mm). For example, the wafer 106 may have a diameter of 4 inches, 5.9 inches (usually referred to as "6 inch", or about 150 mm), 7.9 inches (usually referred to as "8 inches", or about 200 mm), or 11.8 inches. In the example embodiment, the thermally conductive sheet 104 and heat source for the thermally conductive sheet 104 may be modified based on the diameter of the wafer 106. In the example embodiment, the wafer 106 may have a thickness of about 500 μm or less, as heat transfer to wafer surface may be affected by a thicker wafer. The size of the wafer 106 advantageously allows multiple samples, e.g., 108, to be disposed on its surface. The plurality of samples, e.g., 108, may be disposed on the surface of the wafer 106 as an array. Advantageously, this allows the system 100 to measure multiple samples, e.g., 108, in the same measurement cycle, thereby resulting in a reduction of the experiment time, the man-hours and the error rate compared to the conventional approach to thermoelectric metrology. The wafer 106 also advantageously allows samples, e.g., 108, with different form factors to be placed thereon. In particular, a sufficiently large wafer surface enables multiple or larger samples to be placed simultaneously. Due to the wider temperature and size tolerance of a large wafer (with a diameter of at least 4 inches), the wafer 106 may ensure uniform temperature distribution across its surface, even for irregularly shaped samples. The wafer 106 may be a silicon wafer or a quartz wafer.

In the example embodiment, the sample 108 may be a thermoelectric material in the form of a thin film. The sample 108 may have different shapes, e.g., rectangular shape, square shape, or circular shape. The dimensions of a thin-film sample for thermoelectric transport characterization measurement typically depend on the measurement setup and equipment. The sample 108 may be dimensioned to allow for a balance between ease of handling, measurability of signals, and compatibility with the setup of the system 100.

In the example embodiment, the sample 108 may have a thickness falling in the range of from about 10 nm to about 10,000 nm (or 10 μm). The thickness of the sample 108 may fall in the range with start and end points selected from the following group of numbers: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000,

6500, 7000, 7500, 8000, 8500, 9000, 9500, and 10,000 nm. In some examples, the thin film may be in the nanometer range of about 10 nm to about 1000 nm. In some examples, thin films thicker than 1000 nm (or 1 μm) may tend to behave like bulk materials. In general, the thickness of the sample 108 depends on its characteristics. If the sample is conductive, a relatively thinner film may be acceptable; however, if the sample is resistive, a thicker film may be required.

In the example embodiment, the sample 108 may have a length (along the direction of the temperature gradient) of no less than about 10 mm. That is, the length of the sample 108 may be aligned to be substantially parallel to the direction of the temperature gradient. The length (along the direction of the temperature gradient) of the sample 108 may fall in the range with start and end points selected from the following group of numbers: 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, and 50 mm. In some examples, the length of the sample 108 is sufficiently long to establish a measurable temperature gradient. In some examples, a longer length may improve measurement accuracy by producing a larger voltage signal.

In the example embodiment, the sample 108 may have a width falling in the range of from about 1 mm to about 5 mm. The width of the sample 108 may fall in the range with start and end points selected from the following group of numbers: 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 mm. In some examples, the width of the sample 108 may be sufficiently wide to ensure stable electrical and thermal contacts. In some examples, the width of the sample 108 may be sufficiently narrow to reduce thermal losses.

FIG. 2 is a schematic diagram of a stage / temperature control stage / temperature gradient heating stage 200 in an example embodiment. The temperature control stage 200 is constructed in a similar manner to the temperature control stage 102 of FIG. 1.

In the example embodiment, the temperature control stage 200 comprises a thermally conductive sheet / heater plate 202 dimensioned to support a wafer 204 having a diameter of at least 4 inches and a plurality of samples, e.g., 206, disposed on a surface thereof. For example, the thermally conductive sheet 202 may be an aluminum sheet / plate. The temperature control stage 200 is configured to introduce and maintain a temperature gradient across the wafer 204 with the plurality of samples, e.g., 206.

In the example embodiment, the temperature control stage 200 may be configured to introduce and maintain multiple temperature gradients to facilitate thermoelectric transport characterization of the plurality of samples, e.g., 206. For example, the temperature control stage 200 may be configured to introduce and maintain a first temperature gradient, a second
5 temperature gradient, and a third temperature gradient, wherein the three temperature gradients are different from one another. Electrical measurements may be performed on the plurality of samples, e.g., 206 at these three temperature gradients to facilitate determination of one or more thermoelectric properties of the plurality of samples, e.g., 206. It will be appreciated that while temperature gradients are required for measuring thermoelectric
10 properties such as the Seebeck coefficient, they may not be required for electrical conductivity measurements. In the example embodiment, when taking measurements for determining electrical conductivity, the temperature gradient may be small ($\sim 1\text{-}2\text{ K}$), leading to a negligible offset voltage at zero current (in the μV range). This offset voltage does not significantly affect I-V measurements and can be removed during the slope calculation from the I-V curve.
15 Therefore, the characterization process accounts for both thermoelectric and electrical conductivity properties under appropriate conditions.

In the example embodiment, the temperature control stage 200 further comprises a thermoelectric device 208 coupled to one end of the thermally conductive sheet 202 for
20 providing localized heating, and a heat sink 210 coupled to an opposite end of the thermally conductive sheet 202 for maintaining the opposite end of the thermally conductive sheet at room temperature. The temperature gradient may be imposed across the entire thermally conductive sheet 202, e.g., aluminum plate, by localized heating using the thermoelectric device 208 on one side, while the opposite end is maintained at room temperature using the
25 heat sink 210. The thermoelectric device 208 utilizes thermoelectric effects (such as the Peltier effect and the Seebeck effect) for heating, cooling, or energy generation. For example, the thermoelectric device 208 may be a Peltier module that transfers heat using the Peltier effect. A Peltier module may be suitable for providing localized heating in the presently disclosed system due to its form factor, temperature stability, and relatively fast response times. For
30 example, the thermoelectric device 208 may comprise one or more Peltier modules, e.g., a system of 4 Peltier modules connected in series.

In the example embodiment, the temperature control stage 200 is communicatively coupled to a heater controller system 212 configured to drive / power the thermoelectric
35 device, e.g., Peltier module 208, e.g., by controlling a flow of current to the Peltier module 208.

The heater controller system 212 is comprised in a processing unit 214 (compare 114 of FIG. 1). The heater controller system 212 may be a motor driver integrated circuit (IC). The processing unit 214 is configured to control the heater controller system 212 using a signal, e.g., a pulse-width modulation (PWM) signal. The signal may be generated by a control /
5 feedback loop algorithm configured to maintain the temperature at the thermally conductive sheet 202 at a desired level, based on actual temperatures measured at the thermally conductive sheet 202. For example, the feedback loop algorithm may be a proportional-integral-derivative (PID) algorithm.

10 In the example embodiment, the temperature control stage 200 further comprises a first sensor 216 and a second sensor 218 coupled / attached to opposite ends of the thermally conductive sheet 202. The sensors 216, 218 are configured to measure surface temperatures at the respective ends of the thermally conductive sheet 202. The surface temperatures measured by the sensors 216, 218 are transmitted to the processing unit 214 as feedback for
15 the feedback loop algorithm. The sensors 216, 218 may be any suitable devices for measuring temperature. For example, the sensors 216, 218 may be a pair of thermocouple sensors.

For example, the temperature control stage 200 may be custom-built to enforce a precise temperature gradient across the length of the sample 206. Finite element modelling
20 (FEM) of the temperature control stage 200 consisting of the thermally conductive sheet 202, e.g., a thin aluminum sheet backed by an insulating medium, coupled with the thermoelectric device 208, e.g., Peltier thermoelectric generator (TEG) modules, and heat sinks 210 on opposite ends, ensures that the desired temperature difference ΔT is obtained precisely at each sample location. The automated feedback loop algorithm, e.g., PID control loop, also
25 ensures that precise and repeatable experiments can be easily performed under different thermal environments. The aluminum sheet has a high thermal conductivity, thus enforcing the thermal gradient across the wafer which has low thermal conductivity. The temperature control stage 200 is advantageously capable of generating a thermal gradient across a thin aluminum sheet with active heating/passive cooling.

30 During operation of the temperature control stage 200, the processing unit 214, e.g., Raspberry Pi (RPI), sends a signal, e.g., PWM signal, to the heater controller system 210, e.g., L298N motor driver IC, for driving the thermoelectric device 208. The heater controller system 212 drives the thermoelectric device 208, e.g., a system of 4 Peltier modules in series,
35 to impose a temperature gradient across the entire thermally conductive sheet 202, e.g.,

aluminum plate, by localized heating on one side of the thermally conductive sheet 202, while the opposite side of the thermally conductive sheet 202 is maintained at room temperature using the heat sink 210. The first and second sensors 216, 218 measure the actual temperatures at respective ends of the surface of the thermally conductive sheet 202 and
5 transmit the measured temperatures to the feedback loop algorithm in the processing unit 212. The feedback loop algorithm compares the measured temperatures to the desired temperature gradient and calculates how much power the thermoelectric device 208 needs to apply to achieve the desired temperature gradient. The feedback loop algorithm generates an updated signal representing the calculated power level. For example, where the updated
10 signal is a PWM signal, the feedback loop algorithm may adjust the characteristics of the PWM signal, e.g., duty cycle, frequency, voltage amplitude, current limit, waveform shape, pulse duration. The updated signal is sent to the heater controller system 212, which adjusts a current supplied to the thermoelectric device 208. Based on the current from the heater controller system 212, the thermoelectric device 208 heats or cools the thermally conductive
15 sheet 202 to achieve and maintain the desired temperature gradient across the wafer 204 with the plurality of samples, e.g., 206.

In the example embodiment, the design of the temperature control stage 200 is driven by extensive computer simulation and modelling, and advantageously allows the generation
20 of a stable and measurable temperature gradient across the sample surface.

FIG. 3 is a schematic diagram showing a perspective view of a system 300 for performing automated screening of thermoelectric materials in an example embodiment. The system 300 comprises a stage / temperature control stage 302 for introducing a thermal /
25 temperature gradient, said temperature control stage 302 comprising a thermally conductive sheet 304 dimensioned to support a wafer 306 having a diameter of at least 4 inches and a plurality of samples, e.g., 308, disposed on a surface thereof. The system 300 further comprises a thermal camera 310 for measuring a temperature profile along the wafer 306 and a temperature gradient across each sample 308 disposed on the wafer 306. The system 300
30 further comprises an electrical probe 312 for performing electrical measurements on the plurality of samples, e.g., 308 (e.g., when subjected to the temperature gradient). The system 300 further comprises a processing unit 314 for determining one or more thermoelectric properties of the plurality of samples, e.g., 308, based on the electrical measurements. In the example embodiment, the electrical probe 312 is configured to move, in response to

instructions from a vision algorithm, to target locations associated with the plurality of samples, e.g., 308. The system 300 is constructed in a similar manner to the system 100 of FIG. 1.

In the example embodiment, the system 300 further comprises a probe deployment
5 actuator / probe deployment platform 316 configured to move the electrical probe 312 along multiple axes of translation. The probe deployment actuator 316 is coupled to the electrical probe 312 and is configured to move the electrical probe 312 along three axes of translation, e.g., at least two of three axes of translation, to the target locations associated with the plurality of samples, e.g., 308. For example, the probe deployment actuator 316 may be a 3-axis
10 computer numerical control (CNC) probe. The probe deployment actuator 316 comprises a first linear stage 318, a second linear stage 320, and a third linear stage 322. The first linear stage 318 is operable to move the electrical probe 312 along a first axis, e.g., X-axis, as depicted by first bidirectional arrow 324. The second linear stage 320 is operable to move the electrical probe 312 along a second axis, e.g., Y-axis, as depicted by second bidirectional
15 arrow 326. The third linear stage 322 is operable to move the electrical probe 312 along a third axis, e.g., Z-axis, as depicted by third bidirectional arrow 328. The first and second linear stages 318, 320 provide translation in an X-Y plane / horizontal plane to move the electrical probe 312 to different samples, e.g., 308, disposed on the wafer 306. The third linear stage 322 provides vertical translation along the Z-axis to allow the electrical probe 312 to contact
20 the sample 308 for measurement. The third linear stage 322 is configured to receive the electrical probe 312. The probe deployment actuator 316 is a motorized platform. Each of the first, second and third linear stages 318, 320 and 322 may be driven by a motor, e.g., micro-stepper motor (not shown). Stepper motors are motors designed to move in precise increments or "steps" which makes them suitable for applications requiring accurate
25 positioning. It will be appreciated that other configurations of the probe deployment actuator may be used to move the electrical probe.

In the example embodiment, an interface connector 330 may be provided to allow the electrical probe 312 to interface with the third linear stage 322. For example, the interface
30 connector 330 may be a custom-made 3D printed connector. Advantageously, the modular design of the third linear stage 322 allows for different probes to be affixed to thereon, making the probe deployment actuator 316 highly customizable.

In the example embodiment, the probe deployment actuator 316 is configured to
35 automatically move the electrical probe 312 to target locations associated with the plurality of

samples, e.g., 308. The probe deployment actuator 316 may operate through a serial interface to accept instructions from the vision algorithm and guide the electrical probe 312 to the correct position, e.g., a target location associated with the sample 308.

5 In the example embodiment, the electrical probe 312 may be a four-probe system /
four-point probe for performing electrical and thermoelectric, e.g., open circuit voltage,
measurements. The four-point probe 312 comprises four equally spaced probes, i.e., a first
probe 332A, a second probe 332B, a third probe 332C, and a fourth probe 332D. The four
10 probes 332A-332D may be arranged linearly along a straight line and spaced equidistant from
each other. The four probes 332A-332D may have a spacing of about 0.5 mm, about 1 mm,
about 1.5 mm, about 2 mm, about 2.5 mm, about 3 mm, about 3.5 mm, about 4 mm, about
4.5 mm, or about 5 mm between any two immediately adjacent probes. In some examples,
the four probes, e.g., 332, have a spacing of about 2.5 mm. The two outer probes 332A and
15 332D may be configured to measure the open circuit voltage, e.g., open circuit voltage across
the sample 308 due to the temperature gradient. All four probes 332A-332D may be configured
for 4-point resistance measurement. In the example embodiment, using the four-point probe
may advantageously eliminate contact resistance, reduce lead resistance effects, and ensure
uniform current distribution by separating current injection and voltage measurements, reduce
20 error from non-uniform contact, improve reproducibility of results across multiple samples or
measurements, and enables thin film and surface measurements.

 In the example embodiment, the system 300 further comprises a source measure unit
/ electrical source measure unit 334 for performing the electrical and Seebeck measurements.
The electrical measurements may comprise a sheet resistance of each sample when
25 subjected to the temperature gradient, and an open circuit voltage of each sample when
subjected to the temperature gradient. The source measure unit 334 comprises terminals for
connecting to the electrical probe 312, e.g., four-point probe. The source measure unit 334 is
communicatively coupled to the processing unit 314. The source measure unit 334 may be
connected to the same network as the processing unit 314.

30 In the example embodiment, the thermal camera 310 may be an infrared (IR) camera
configured to use IR imaging to detect heat emitted by the wafer 306 with the plurality of
samples, e.g., 308. The thermal camera 310 may be configured to generate a thermal map /
profile of the wafer 306, providing a visualization of temperature distribution across the wafer
35 306 and the plurality of samples, e.g., 308, disposed thereon. The thermal camera 310 may

be configured to compute the temperature gradient across the wafer by analyzing the spatial variation in temperature. The thermal camera 310 may be a high-resolution IR camera equipped with a high-resolution IR sensor array to capture fine details of temperature variation. The thermal camera 310 may be capable of generating a thermal image with an image
5 resolution of about $X \times Y$ pixels (px), where X and Y are selected from the following group of numbers of pixels: 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500, 520, 540, 560, 580, 600, 620, and 640 px. The thermal camera 310 may be capable of generating a thermal image with a temperature
10 resolution of no more than 0.1 K, no more than 0.2 K, no more than 0.3 K, no more than 0.4 K, no more than 0.5 K, no more than 0.6 K, no more than 0.7 K, no more than 0.8 K, no more than 0.9 K, or no more than 1 K. For example, the thermal camera 310 may be capable of generating an 80×60 px thermal image with a temperature resolution of 0.1 K. Advantageously, the thermal camera 310 may provide a fast, non-contact, and high-throughput temperature measurement tool that maps temperature profiles and gradients over
15 the wafer 308 and allows for visual inspection of the gradients.

In the example embodiment, the thermal camera 310 is coupled to the processing unit 314. The thermal camera 310 may be controlled by the processing unit 314 using a suitable programming language, e.g., Python. The thermal camera 310 may support a client/server
20 protocol for data communication between electronic devices, e.g., industrial MODBUS protocol. That is, the thermal camera 310 may be controlled and queried over a network using the MODBUS protocol, making it compatible with industrial automation systems. The processing unit 314 may comprise a library / software library to interface with the thermal camera 310 using the programming language, e.g., Python code. The library may allow users
25 to retrieve thermal images or temperature measurements from the thermal camera 310. The library may also allow users to remote configure the thermal camera 310, e.g., setting temperature ranges, calibration settings, or resolution. In the example embodiment, the processing unit 314 may utilize an interpolation scheme for estimating temperature values at locations where the thermal camera 310 cannot directly measure (e.g., spot under the
30 electrical probe 312 due to positioning of the thermal camera 310 relative to the electrical probe 312 and field of view constraints). The interpolation scheme advantageously allows an actual temperature difference ΔT to be extracted from available measurements.

In the example embodiment, the thermal camera 310 is further configured to provide
35 a visual/thermal feed for the vision algorithm. Advantageously, the thermal camera 310 offers

the dual benefits of temperature metrology for rapid in-plane temperature measurements as well as a visual feed for the imaging processing algorithms that guide the electrical probe 312.

5 In the example embodiment, the vision algorithm may comprise capturing an image of the plurality of samples, e.g., 308, using the thermal camera 310. The thermal camera 310 may capture a top-down image of the plurality of samples, e.g., 308, thereby obtaining a 2D thermal map that reflects in-plane temperature distributions.

10 In the example embodiment, the vision algorithm may further comprise performing image recognition on the captured image to identify the plurality of samples, e.g., 308, and to spatially index sample arrays. Spatially indexing sample arrays may comprise assigning a unique identifier or coordinate to each sample 308 in an array based on its physical location within the array. This enables the vision algorithm to recognize, locate, and interact with individual samples, e.g., 308, in a structured and systematic manner. In the example
15 embodiment, the step of performing image recognition on the captured image may comprise performing image registration on the captured image by detecting the wafer 306. The step of performing image recognition on the captured image may further comprise performing image thresholding on the captured image to binarize the captured image. The step of performing image recognition on the captured image may further comprise performing edge detection on
20 the binarized image to identify sample boundaries. The step of performing image recognition on the captured image may further comprise performing blob detection on the binarized image to locate sample positions for subsequent measurements. Advantageously, blob detection is a particularly robust image recognition technique that is stable against shape translation and transformation, making it useful for finding irregular samples.

25 In the example embodiment, the vision algorithm may further comprise transmitting instructions / computer program instructions to the probe deployment actuator 316 based on data obtained from the image recognition step. The instructions may be transmitted through a serial interface to guide the electrical probe 312 to the correct position, e.g., target location
30 associated with the sample 308. The instructions may be transmitted to a motor controller, e.g., an Arduino UNO microcontroller, comprised within processing unit 314. The motor controller may be configured to transmit instructions to the motors, e.g., stepper motors, of the linear stages 318, 320, 322 to perform linear motion along the three axes or directions 324, 326, 328, thereby moving the electrical probe 312 to the target locations associated with the
35 plurality of samples, e.g., 308. The motor controller may be configured to transmit instructions

to the motors via electronic components that act as intermediaries (i.e., intermediary electronic components) between the motor controller and the motors. The intermediary electronic components may include, for example stepper motor driver chips or micro-stepping drivers. Micro-stepping drivers allow the motors to move in smaller steps than their default step size, increasing the precision of movement. The intermediary electronic components may be configured to receive command signals (electrical signals) from the motor controller and to convert the command signals into motor-compatible control signals. The intermediary electronic components may also be configured to manage a supply of current and voltage to the motors to ensure smooth operation and prevent damage. The intermediary electronic components may be capable of micro-stepping, e.g., 1/32 micro-stepping, giving the probe position a spatial precision or spatial resolution of e.g., about 50 picometers (pm).

In the example embodiment, the system 300 may enable automated high-throughput screening of thermoelectric materials. The system 300 may advantageously provide an alternative solution for thermoelectric transport characterization, by requiring minimal processing and enabling the measurement of multiple samples within the same cycle. The results from this rapid screening process can be used to identify promising samples with higher power factor, which can then be selected for thermal analysis to determine the figure of merit ZT . The system 300 may advantageously implement an automated measurement cycle capable of measuring multiple samples within a single cycle, thereby reducing experiment time, manual labor, and error rate compared to conventional thermoelectric metrology methods. In addition, the measurement of the Seebeck coefficient can be used via analysis using Boltzmann Transport Equations to extract the doping level of semiconducting thin films.

FIG. 4 is a schematic flowchart 400 illustrating a method of performing automated screening of thermoelectric materials in an example embodiment. At step 402, a wafer having a diameter of at least 4 inches and a plurality of samples disposed on a surface thereof is provided. At step 404, the wafer is positioned on a thermally conductive sheet of a temperature control stage and a temperature gradient is introduced. At step 406, a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer are measured using a thermal camera. At step 408, electrical measurements, e.g., open circuit voltage measurements are measured using an electrical probe on the plurality of samples (e.g., when subjected to the temperature gradient). At step 410, the electrical probe is moved, in response to instructions from a vision algorithm, to target locations associated with the

plurality of samples. At step 412, one or more thermoelectric properties of the plurality of samples are determined based on the electrical measurements using a processing unit.

In the example embodiment, the method may allow users to perform an automated
5 high-throughput experiment involving the characterization of multiple samples. The experiment process is fully automated from the point of loading the sample to obtaining the results. Computer vision algorithms are used to guide the electrical probe to the correct locations. The processing unit is used to integrate the data collection and experiment management steps into a computer executable program, e.g., Python script.

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FIG. 5 is a photograph of a system 500 for performing automated screening of thermoelectric materials in an example embodiment. The system 500 is constructed in a similar manner to the system 100 of FIG. 1 and system 300 of FIG. 3. The system 500 comprises a heater and process control system 502 (compare 302 of FIG. 3), a thermal
15 camera 504 (compare 310 of FIG. 3), a probe arrangement 506 (compare 312 of FIG. 3), and a source measure unit 508, e.g., Keithley 2450 Source Meter (compare 334 of FIG. 3). The heater and process control system 502 is constructed in a similar manner to the temperature control stage 200 of FIG. 2.

In the example embodiment, the system 500 is configured to measure a room
20 temperature Seebeck coefficient and an electrical conductivity (or electrical resistivity which is inversely related to electrical conductivity) for thin-film samples 510 positioned on a 4-inch wafer placed on a test bed / heater plate, e.g., an aluminum plate (compare 304 of FIG. 3). The system 500 utilizes a differential steady state measurement regime, where an open circuit
25 voltage for each sample is measured at three different, stable, values of temperature difference ΔT . Additionally, the electrical conductivity of the sample 510 is measured using a 4-point probe method. The system 500 may advantageously allow simultaneous measurement of Seebeck coefficient and electrical conductivity at any location on the sample surface.

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In the example embodiment, a temperature gradient is imposed across the entire aluminum plate by localized heating on one side, while the opposite end is maintained at room temperature using a heat sink (compare 210 of FIG. 2). The localized heating is implemented using a thermoelectric device, e.g., a system of 4 Peltier modules in series (compare 208 of
35 FIG. 2), which are selected for their form factor, temperature stability and fast response times.

The Peltier modules are driven by a heater controller system, e.g., an L298N motor driver IC (compare 212 of FIG. 2), which is controlled using a pulse-width modulation (PWM) signal from a processing unit, e.g., Raspberry Pi (RPi) (compare 214 of FIG. 2). This PWM signal is, in turn, generated by a proportional-integral-derivative (PID) algorithm, based on the
5 temperature reported by two thermocouple sensors (compare 216 and 218 of FIG. 2) attached to the heater plate.

In the example embodiment, temperature measurement is performed using the thermal camera 504, e.g., a high-resolution IR camera, which generates an 80×60 px thermal
10 image with a temperature resolution of 0.1 K. FIG. 6 shows a thermal image of the 4-inch wafer with a plurality of samples disposed on its surface in an array. The thermal image depicts different shades each corresponding to a specific temperature range. Region 1 depicts a shade representing a hotter (higher temperature) region due to its proximity to the localized heating by the Peltier modules. Region 2 depicts a second shade representing a warm
15 temperature region, i.e., lower temperature than region 1. Region 3 depicts a third shade representing a moderate temperature region, i.e., lower temperature than region 2. Region 4 depicts a fourth shade representing a cooler temperature region, i.e., lower temperature than region 3, due to cooling by heat sinks. FIG. 7 shows a thermal gradient map of the 4-inch wafer from an ANSYS simulation. Similar to FIG. 6, the thermal gradient map of the 4-inch
20 wafer depicts a transition of temperature from hotter to cooler temperatures in the direction of the arrow, as the shades of the map change from the first to the fourth shades.

In the example embodiment, the thermal camera 504 supports an industrial MODBUS protocol, and a library is written to fetch data from the thermal camera 504 and to adjust its
25 settings remotely using Python code. As the resolution of the thermal camera 504 is limited, and a direct view of the spot under the probe 506 is not available, an interpolation method / scheme is devised in order to extract the actual ΔT from the available measurements. FIG. 8 is a graph illustrating a linearly fitted line and an exponentially fitted line, generated using an interpolation method to estimate temperatures at surface locations of a sample in an example
30 embodiment.

In the example embodiment, the probe arrangement 506 comprising a 4-probe system (compare 312 of FIG. 3) with a spacing of 2.5 mm between the probes (compare 332A-332D of FIG. 3) is used for electrical measurements. This setup is mounted on a custom-made, 3D
35 printed apparatus designed to be able to interface with a 3-axis CNC machine. The CNC

operates through a serial interface to accept instructions and guide the probes to the correct position. The four probes are connected to a front panel of the electrical source-measure unit (SMU) 508, which is responsible for measuring the open circuit voltage by two outer probes as well as for carrying out the 4-point resistance measurement. The SMU 508 is connected to the same network as the Raspberry Pi, and operations are controlled using a Python implementation of the Standard Commands for Programmable Instruments (SCPI) protocol commonly used in scientific instruments. The scanning electrical probe arrangement in the presence of a thermal gradient advantageously allows the measurement of electrical properties at any point on the wafer surface while a controlled temperature differential is present.

In the example embodiment, experiment and process control of the entire experiment cycle is coordinated using the Raspberry Pi as the central computer. As the SMU 508 and the thermal camera 504 are present in the same local network, the RPi is able to retrieve data from these instruments through a Python script. Additionally, on-board PWM and Serial Peripheral Interface (SPI) channels of the RPi are used to implement the heater controller system, which is moderated using a PID algorithm based on temperature readings from a pair of thermocouples on the heater plate surface. FIG. 9 shows temperature variation along the 4-inch wafer. Temperatures at different points are measured by the thermocouple and the solid line shows an interpolation curve to deduce the temperature at different points on the wafer. FIG. 10 shows the temperature profile across the quartz wafer by the thermal camera 504. The quartz wafer is demarcated by a circle with dotted lines.

In the example embodiment, signal processing and parameter extraction are based on the steady-state measurement scheme, which is used to obtain a stable and reliable measurement of the Seebeck coefficient. This is achieved by using the PID controller to set the hot-side temperature at multiple fixed points until the steady state is reached, and then measuring the corresponding open-circuit voltage with the two outer probes of the probe arrangement 506. Since the temperature profile across the wafer surface is known, it can be modelled as an exponentially decaying function, and the temperature difference between those two outer probes can be extracted where the open circuit voltage was measured.

In the example embodiment, for each temperature step, 3 minutes of open circuit voltage and ΔT data is collected at the steady-state as shown in FIG. 11 and is averaged to produce one data point for the final Seebeck coefficient measurement as depicted in FIG. 12.

Three open circuit voltage points were taken at three different ΔT . As per the steady-state measurement methodology, the slope of a linear fit to these three data points gives the Seebeck coefficients of the Sb_2Te_3 thin film. Since the system uses a 4-probe configuration, the sheet resistance can also be measured at each step using the 4PP method as shown in FIG. 13. Once the thickness of the film is known, conductivity can be calculated using formula, $\sigma = \frac{1}{AR_{st}}$, where A is geometrical factor and t is the thickness of the film.

In the example embodiment, the methodology of measuring the Seebeck coefficient of a sample is compared with existing commercial measurement equipment. The methodology was observed to produce good results when compared with conventional systems such as the ZEM-3. ZEM-3 is a large measurement system capable of accurately measuring the Seebeck coefficient and electrical conductivity for a single sample at a time, but sample preparation and measurement is typically time-consuming due to requirements on the sample form-factor. The system 500 is observed to consistently return measurements within 15% of the ZEM-3 at a fraction of the measurement time and on 4" wafer size, which is impossible with current commercially available devices.

In the described example embodiments, the presently disclosed system and method of performing automated screening of thermoelectric materials may enable fast and accurate measurement of thermoelectric properties, e.g., Seebeck coefficient and electrical conductivity of thin-film thermoelectric samples. In the described example embodiments, the electrical probe, e.g., a 3-axis translational CNC probe allows the system to automatically measure multiple samples on the stage, guided by a computer vision algorithm processing IR video from a thermal camera feed. In the described example embodiments, the stage with feedback loop algorithm, e.g., PID-controlled heating and cooling elements at opposite edges enforces a temperature gradient across the wafer substrate and the thermal camera performs precise measurements of the temperature difference ΔT across individual samples. In the described example embodiments, the electrical probe, e.g., a four-point probe first measures the open-circuit potential across the thin film caused by the temperature gradient, and subsequently measures the electrical conductivity to yield the Seebeck coefficient in a single step. Advantageously, the ability to perform measurements of temperature, potential, and current simultaneously enables automated, high-throughput screening for optimum thermoelectric properties of many diverse materials and form-factors.

In the described example embodiments, the presently disclosed system and method may enable automated high-throughput measurement with sample detection. The presently disclosed system and method may advantageously enable accurate measurements of thermoelectric properties (the measurements differ by less than 15% compared to measurements obtained from commercial instrument). The presently disclosed system and method may advantageously allow an expanded range of form factors such as thin film samples to be tested. The presently disclosed system and method may advantageously facilitate high speed measurement of samples (more than 10 times faster compared to commercial instrument). The presently disclosed system and method may be used in applications related to high throughput screening of thermoelectric materials, and study of thermoelectric properties of materials under different temperature conditions.

The terms "coupled" or "connected" as used in this description are intended to cover both directly connected or connected through one or more intermediate means, unless otherwise stated.

The description herein may be, in certain portions, explicitly or implicitly described as algorithms and/or functional operations that operate on data within a computer memory or an electronic circuit. These algorithmic descriptions and/or functional operations are usually used by those skilled in the information/data processing arts for efficient description. An algorithm is generally relating to a self-consistent sequence of steps leading to a desired result. The algorithmic steps can include physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transmitted, transferred, combined, compared, and otherwise manipulated.

Further, unless specifically stated otherwise, and would ordinarily be apparent from the following, a person skilled in the art will appreciate that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", and the like, refer to action and processes of an instructing processor/computer system, or similar electronic circuit/device/component, that manipulates/processes and transforms data represented as physical quantities within the described system into other data similarly represented as physical quantities within the system or other information storage, transmission or display devices etc.

The description also discloses relevant device/apparatus for performing the steps of the described methods. Such apparatus may be specifically constructed for the purposes of the methods, or may comprise a general purpose computer/processor or other device selectively activated or reconfigured by a computer program stored in a storage member. The
5 algorithms and displays described herein are not inherently related to any particular computer or other apparatus. It is understood that general purpose devices/machines may be used in accordance with the teachings herein. Alternatively, the construction of a specialized device/apparatus to perform the method steps may be desired.

10 In addition, it is submitted that the description also implicitly covers a computer program, in that it would be clear that the steps of the methods described herein may be put into effect by computer code. It will be appreciated that a large variety of programming languages and coding can be used to implement the teachings of the description herein. Moreover, the computer program if applicable is not limited to any particular control flow and
15 can use different control flows without departing from the scope of the invention.

Furthermore, one or more of the steps of the computer program if applicable may be performed in parallel and/or sequentially. Such a computer program if applicable may be stored on any computer readable medium. The computer readable medium may include
20 storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a suitable reader/general purpose computer. In such instances, the computer readable storage medium is non-transitory. Such storage medium also covers all computer-readable media e.g. medium that stores data only for short periods of time and/or only in the presence of power, such as register memory, processor cache and Random Access
25 Memory (RAM) and the like. The computer readable medium may even include a wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in Bluetooth technology. The computer program when loaded and executed on a suitable reader effectively results in an apparatus that can implement the steps of the described methods.

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The example embodiments may also be implemented as hardware modules. A module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using digital or discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated

Circuit (ASIC). A person skilled in the art will understand that the example embodiments can also be implemented as a combination of hardware and software modules.

Additionally, when describing some embodiments, the disclosure may have disclosed
5 a method and/or process as a particular sequence of steps. However, unless otherwise
required, it will be appreciated the method or process should not be limited to the particular
sequence of steps disclosed. Other sequences of steps may be possible. The particular order
of the steps disclosed herein should not be construed as undue limitations. Unless otherwise
required, a method and/or process disclosed herein should not be limited to the steps being
10 carried out in the order written. The sequence of steps may be varied and still remain within
the scope of the disclosure.

Further, in the description herein, the word "substantially" whenever used is
understood to include, but not restricted to, "entirely" or "completely" and the like. In addition,
15 terms such as "comprising", "comprise", and the like whenever used, are intended to be non-
restricting descriptive language in that they broadly include elements/components recited after
such terms, in addition to other components not explicitly recited. For an example, when
"comprising" is used, reference to a "one" feature is also intended to be a reference to "at least
one" of that feature. Terms such as "consisting", "consist", and the like, may, in the appropriate
20 context, be considered as a subset of terms such as "comprising", "comprise", and the like.
Therefore, in embodiments disclosed herein using the terms such as "comprising", "comprise",
and the like, it will be appreciated that these embodiments provide teaching for corresponding
embodiments using terms such as "consisting", "consist", and the like. Further, terms such as
"about", "approximately" and the like whenever used, typically means a reasonable variation,
25 for example a variation of +/- 5% of the disclosed value, or a variance of 4% of the disclosed
value, or a variance of 3% of the disclosed value, a variance of 2% of the disclosed value or
a variance of 1% of the disclosed value.

Furthermore, in the description herein, certain values may be disclosed in a range. The
30 values showing the end points of a range are intended to illustrate a preferred range.
Whenever a range has been described, it is intended that the range covers and teaches all
possible sub-ranges as well as individual numerical values within that range. That is, the end
points of a range should not be interpreted as inflexible limitations. For example, a description
of a range of 1% to 5% is intended to have specifically disclosed sub-ranges 1% to 2%, 1% to
35 3%, 1% to 4%, 2% to 3% etc., as well as individually, values within that range such as 1%,

2%, 3%, 4% and 5%. The intention of the above specific disclosure is applicable to any depth/breadth of a range.

5 Different example embodiments can be implemented in the context of data structure, program modules, program and computer instructions executed in a computer implemented environment. A general-purpose computing environment is briefly disclosed herein. One or more example embodiments may be embodied in one or more computer systems, such as is schematically illustrated in FIG. 15.

10 One or more example embodiments may be implemented as software, such as a computer program being executed within a computer system 1500, and instructing the computer system 1500 to conduct a method of an example embodiment.

15 The computer system 1500 comprises a computer unit 1502, input modules such as a keyboard 1504 and a pointing device 1506 and a plurality of output devices such as a display 1508, and printer 1510. A user can interact with the computer unit 1502 using the above devices. The pointing device can be implemented with a mouse, track ball, pen device or any similar device. One or more other input devices (not shown) such as a joystick, game pad, satellite dish, scanner, touch sensitive screen or the like can also be connected to the
20 computer unit 1502. The display 1508 may include a cathode ray tube (CRT), liquid crystal display (LCD), field emission display (FED), plasma display or any other device that produces an image that is viewable by the user.

25 The computer unit 1502 can be connected to a computer network 1512 via a suitable transceiver device 1514, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN) or a personal network. The network 1512 can comprise a server, a router, a network personal computer, a peer device or other common network node, a wireless telephone or wireless personal digital assistant. Networking environments may be found in offices, enterprise-wide computer networks and
30 home computer systems etc. The transceiver device 1514 can be a modem/router unit located within or external to the computer unit 1502, and may be any type of modem/router such as a cable modem or a satellite modem.

35 It will be appreciated that network connections shown are exemplary and other ways of establishing a communications link between computers can be used. The existence of any

of various protocols, such as TCP/IP, Frame Relay, Ethernet, FTP, HTTP and the like, is presumed, and the computer unit 1502 can be operated in a client-server configuration to permit a user to retrieve web pages from a web-based server. Furthermore, any of various web browsers can be used to display and manipulate data on web pages.

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The computer unit 1502 in the example comprises a processor 1518, a Random Access Memory (RAM) 1520 and a Read Only Memory (ROM) 1522. The ROM 1522 can be a system memory storing basic input/ output system (BIOS) information. The RAM 1520 can store one or more program modules such as operating systems, application programs and program data.

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The computer unit 1502 further comprises a number of Input/Output (I/O) interface units, for example I/O interface unit 1524 to the display 1508, and I/O interface unit 1526 to the keyboard 1504. The components of the computer unit 1502 typically communicate and interface/couple connectedly via an interconnected system bus 1528 and in a manner known to the person skilled in the relevant art. The bus 1528 can be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures.

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It will be appreciated that other devices can also be connected to the system bus 1528. For example, a universal serial bus (USB) interface can be used for coupling a video or digital camera to the system bus 1528. An IEEE 1394 interface may be used to couple additional devices to the computer unit 1502. Other manufacturer interfaces are also possible such as FireWire developed by Apple Computer and i.Link developed by Sony. Coupling of devices to the system bus 1528 can also be via a parallel port, a game port, a PCI board or any other interface used to couple an input device to a computer. It will also be appreciated that, while the components are not shown in the figure, sound/audio can be recorded and reproduced with a microphone and a speaker. A sound card may be used to couple a microphone and a speaker to the system bus 1528. It will be appreciated that several peripheral devices can be coupled to the system bus 1528 via alternative interfaces simultaneously.

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An application program can be supplied to the user of the computer system 1500 being encoded/stored on a data storage medium such as a CD-ROM or flash memory carrier. The application program can be read using a corresponding data storage medium drive of a data storage device 1530. The data storage medium is not limited to being portable and can include

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instances of being embedded in the computer unit 1502. The data storage device 1530 can comprise a hard disk interface unit and/or a removable memory interface unit (both not shown in detail) respectively coupling a hard disk drive and/or a removable memory drive to the system bus 1528. This can enable reading/writing of data. Examples of removable memory
5 drives include magnetic disk drives and optical disk drives. The drives and their associated computer-readable media, such as a floppy disk provide nonvolatile storage of computer readable instructions, data structures, program modules and other data for the computer unit 1502. It will be appreciated that the computer unit 1502 may include several of such drives. Furthermore, the computer unit 1502 may include drives for interfacing with other types of
10 computer readable media.

The application program is read and controlled in its execution by the processor 1518. Intermediate storage of program data may be accomplished using RAM 1520. The method(s) of the example embodiments can be implemented as computer readable instructions,
15 computer executable components, or software modules. One or more software modules may alternatively be used. These can include an executable program, a data link library, a configuration file, a database, a graphical image, a binary data file, a text data file, an object file, a source code file, or the like. When one or more computer processors execute one or more of the software modules, the software modules interact to cause one or more computer
20 systems to perform according to the teachings herein.

The operation of the computer unit 1502 can be controlled by a variety of different program modules. Examples of program modules are routines, programs, objects, components, data structures, libraries, etc. that perform particular tasks or implement
25 particular abstract data types. The example embodiments may also be practiced with other computer system configurations, including handheld devices, multiprocessor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing
30 environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

The example embodiments may also be practiced with other computer system
35 configurations, including handheld devices, multiprocessor systems/servers, microprocessor-

based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

It will be appreciated by a person skilled in the art that other variations and/or modifications may be made to the specific embodiments without departing from the scope of the invention as broadly described. For example, in the description herein, features of different exemplary embodiments may be mixed, combined, interchanged, incorporated, adopted, modified, included etc. or the like across different exemplary embodiments. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A system for performing automated screening of thermoelectric materials, the system comprising,
- 5 a temperature control stage for introducing a temperature gradient, said temperature control stage comprising a thermally conductive sheet dimensioned to support a wafer having a diameter of at least 4 inches and a plurality of samples disposed on a surface thereof;
- a thermal camera for measuring a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer;
- 10 an electrical probe for performing electrical measurements on the plurality of samples; and
- a processing unit for determining one or more thermoelectric properties of the plurality of samples based on the electrical measurements;
- wherein the electrical probe is configured to move, in response to instructions from a vision algorithm, to target locations associated with the plurality of samples.
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2. The system according to claim 1, wherein the temperature control stage further comprises,
- a Peltier module coupled to one end of the thermally conductive sheet for providing
- 20 localized heating; and
- a heat sink coupled to an opposite end of the thermally conductive sheet for maintaining the opposite end of the thermally conductive sheet at room temperature.
3. The system according to claim 2, wherein the temperature control stage further
- 25 comprises a heater controller system coupled to the Peltier module, said heater controller system configured to control a flow of current to the Peltier module.
4. The system according to claim 3, wherein the processing unit is configured to control the heater controller system using a pulse-width modulation (PWM) signal generated
- 30 by a proportional-integral-derivative (PID) algorithm.
5. The system according to any one of claims 1 to 4, further comprising a probe deployment actuator coupled to the electrical probe, wherein the probe deployment actuator is configured to move the electrical probe along three axes of translation to the target locations
- 35 associated with the plurality of samples.

6. The system according to any one of claims 1 to 5, further comprising a source measure unit coupled to the electrical probe for performing the electrical measurements, wherein the electrical measurements comprise a sheet resistance of each sample when subjected to the temperature gradient, and an open circuit voltage of each sample when subjected to the temperature gradient.
7. The system according to claim 6, wherein the electrical probe comprises four probes arranged linearly along a straight line and spaced equidistant from each other; wherein two of the probes are configured to measure the open circuit voltage for each sample at multiple temperature gradients; and wherein the four probes are configured to measure the electrical resistance of each sample.
8. The system according to any one of claims 1 to 7, wherein the thermal camera is further configured to provide a thermal feed as input to the vision algorithm for instructing the electrical probe to the target locations.
9. The system according to claim 8, wherein the thermally conductive sheet has a thickness that is tuned to one or more thermal properties of the plurality of samples.
10. The system according to any one of claims 1 to 9, wherein the one or more thermoelectric properties comprises an electrical conductivity of each sample, and a Seebeck coefficient of each sample.
11. A method of performing automated screening of thermoelectric materials, the method comprising, providing a wafer having a diameter of at least 4 inches and a plurality of samples disposed on a surface thereof; positioning the wafer on a thermally conductive sheet of a temperature control stage and introducing a temperature gradient; measuring a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer using a thermal camera;

performing electrical measurements using an electrical probe on the plurality of samples;

moving the electrical probe, in response to instructions from a vision algorithm, to target locations associated with the plurality of samples; and

5 determining one or more thermoelectric properties of the plurality of samples based on the electrical measurements using a processing unit.

12. The method according to claim 11, further comprising,

10 heating one end of the thermally conductive sheet using a Peltier module coupled thereto; and

maintaining an opposite end of the thermally conductive sheet at room temperature using a heat sink coupled thereto.

13. The method according to claim 12, further comprising controlling a flow of

15 current to the Peltier module using a heater controller system coupled thereto.

14. The method according to claim 13, further comprising controlling the heater controller system using a pulse-width modulation (PWM) signal generated by a proportional-integral-derivative (PID) algorithm.

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15. The method according to any one of claims 11 to 14, further comprising moving the electrical probe along three axes of translation to the target locations associated with the plurality of samples using a probe deployment actuator coupled to the electrical probe.

25 16. The method according to any one of claims 11 to 15, further comprising performing the electrical measurements using a source measure unit coupled to the electrical probe, wherein the electrical measurement is a sheet resistance of each sample when subjected to the temperature gradient, and an open circuit voltage of each sample when subjected to the temperature gradient.

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17. The method according to claim 16, wherein the step of measuring electrical and thermoelectric measurements comprises,

35 measuring the open circuit voltage for each sample at multiple temperature gradients using two probes of a four-point probe having four probes arranged linearly along a straight line and spaced equidistant from each other; and

measuring the electrical resistance of each sample using all four probes of the four-point probe.

18. The method according to any one of claims 11 to 17, further comprising
5 providing a thermal feed using the thermal camera as input to the vision algorithm for instructing the electrical probe to the target locations.

19. The method according to claim 18, wherein the thermally conductive sheet has a thickness that is tuned to one or more thermal properties of the plurality of samples.
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20. A non-transitory computer readable storage medium having stored thereon instructions for instructing a method of performing automated screening of thermoelectric materials, the method comprising,

providing a wafer having a diameter of at least 4 inches and a plurality of samples
15 disposed on a surface thereof;

positioning the wafer on a thermally conductive sheet of a temperature control stage for introducing a temperature gradient;

measuring a temperature profile along the wafer and a temperature gradient across each sample disposed on the wafer using a thermal camera;

20 performing electrical measurements using an electrical probe on the plurality of samples;

moving the electrical probe, in response to instructions from a vision algorithm, to target locations associated with the plurality of samples; and

determining one or more thermoelectric properties of the plurality of samples based on
25 the electrical measurements using a processing unit.