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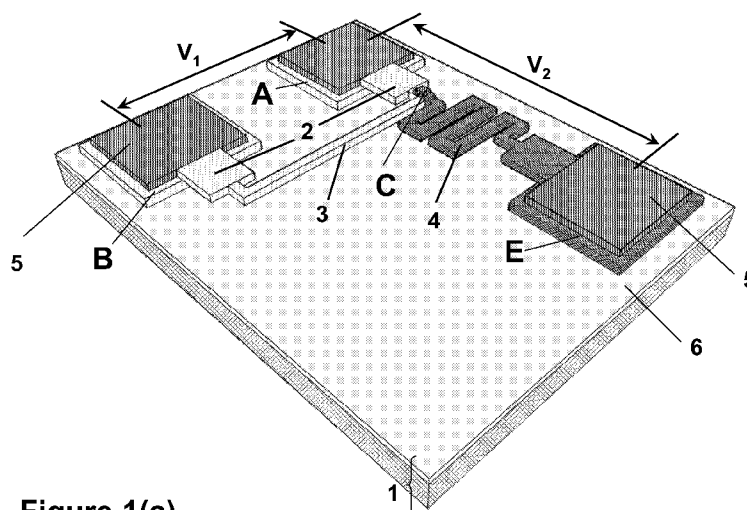


Figure 1(a)

(57) Abstract: A test structure is presented to measure thermal conductivity of thin film materials based on the Seebeck effect. Furthermore, a method for the fabrication of the test structure and a method for measuring the thermal conductivity with the test structure is presented. The test structure is fabricated by surface micromachining technology having the advantage that it can be easily monolithically integrated together with VLSI circuits and MEMS devices.

Thermal conductivity of thin films

Technical field of the invention

5 The invention relates to the field of sensing systems for measuring specific values of thin films.

Background of the invention

10 The thermal conductivity of thin film materials used in electronic devices, such as, e.g. polycrystalline silicon (poly-Si) and polycrystalline silicon germanium (poly-SiGe), is a relevant material property for both very large scale integration (VLSI) circuits and microelectromechanical system (MEMS) devices. With continuous downscaling of the critical dimensions in VLSI circuits, the proper thermal management becomes more important in design, fabrication and packaging. Therefore, the thermal conductivity of thin film materials should be
15 measured precisely. Moreover, the knowledge of the thermal conductivity also plays an important role in the design of a variety of MEMS devices, such as micro actuators, micro chemical sensors, microfluidic systems and micromachined thermopiles. For these devices, the thermal conductivity is an important factor for the device performance either by intentional design or undesirable coupling.

20 However, the thermal conductivity of thin film samples can be largely different from that of bulk samples of the same material. For instance, the thermal conductivity of thin film poly-Si is smaller than that of similarly doped crystalline bulk silicon, by at least a factor of 2. As such there is a need to measure thermal conductivity directly on thin films.

25 Methods for measuring the thermal conductivity of thin film materials fall into two main categories: dynamic methods and static methods.

Dynamic methods usually measure the transient response from the thin film sample material under a certain type of excitation.

30 One frequently used dynamic method is the 3ω method [D. G. Cahill, "Thermal conductivity measurement from 30 to 750 K: the 3ω method", *Rev. Sci. Instrum.*, Vol. 61, No. 2, pp. 802-808, 1990]. This method is often implemented with a 4-terminal thin film metal heater, which is meanwhile employed as a

temperature monitor, patterned on the sample material. When an AC sinusoidal current with frequency ω is injected into the heater, both the generated Joule heat and the temperature increase vary at the frequency 2ω . Because the electrical resistance of the heater is coupled to its temperature according to the temperature coefficient of resistance (TCR), the measured actual electrical resistance has a component fluctuating at the frequency 3ω . By measuring the 3ω components at two different frequencies, the thermal conductivity of the sample material can be calculated.

Another dynamic method measures the optical reflectance at multiple spots on the thin film sample material heated up by an incident laser beam [A. Rosencwaig, J. Opsal, W. L. Smith and D. L. Willenborg, "Detection of thermal waves through optical reflectance", *Appl. Phys. Lett.*, vol. 46, no. 11, pp. 1013-1015, 1985.]. In this method, the thin film sample material is prepared preferably on a substrate with low diffusivity. It is heated up locally by a focused incident laser beam. As the heat spreads radially from the heating spot, the temperature of the sample material increases, leading to the change in the optical reflectivity. Because the optical reflectivity at various spots can be gauged by using a movable probe beam deployed above the sample material, the spatial temperature gradient resulting from the incident laser beam can hence be derived. On the other hand, the power injected into the sample material is known by measuring the difference between the injected laser power and the reflected one. Thus, the lateral thermal conductivity of the thin film material can be calculated.

A static method measures the steady-state response from a micromachined test structure, such as thermal Van der Pauw structure, suspended membrane and suspended cantilever, under thermal excitation [M. von Arx, O. Paul and H. Baltes, "Process-dependent thin -film thermal conductivities for thermal CMOS MEMS", *IEEE J. MEMS*, Vol.9, No.1, pp.136-145, Mar. 2000]. The thermal excitation is usually realized by Joule heating from a thin film resistor. In the best case a large portion of the generated heat is conducted through the sample material (to build up a measurable temperature difference across the sample material) and the thermal losses through the parasitic heat paths, such as air convection, air conduction and materials other than the sample material, are minimized. Often a differential measurement scheme is used, in which thermal measurements are

done on two sets of test structures, i.e. one without and one with the sample material to be measured. Due to the presence of the sample material, the overall thermal conductance from the heat source to the heat sink increases, resulting in a smaller temperature difference under the same heat flow. This temperature difference is usually determined by measuring the change in the electrical resistances of temperature monitors. The temperature monitor is usually made in the form of a thin film resistor from materials with a relatively large temperature coefficient of resistance, TCR, such as doped poly-Si.

CN1445535 presents a test structure for determining the thermal conductivity of poly-Si fabricated by surface micromachining technology with a process compatible with CMOS fabrication. This test structure is based on the TCR measurement principle. This method uses a set of three structures, one is without any cantilever and two are with cantilevers of different lengths. In all three structures a suspended poly-Si stripe is used as a heater, each end of this heater is connected by two interconnects, the first two to apply a first voltage to inject power, the other two to measure another voltage, from which the resistance change can be determined, and based on the poly-Si TCR, the temperature change can be determined as well, thus the thermal conductance of the whole structure can be derived. The same experiment can be done on the other two structures. From the difference between the overall thermal conductances, the thermal conductance of the suspended cantilevers can be determined. Thus with the knowledge in geometries, the thermal conductivity can be calculated. A disadvantage of this method is that the temperature profile in the heater is not homogeneous. Thus the determined ΔT is only the average value over the heater, resulting in inaccuracies of the measurement.

Disclosure of the invention

It is an aim of the current invention to present a test structure and a method using that test structure for determining the thermal conductivity of a thin film material with a higher accuracy.

This aim is achieved according to the invention by the structure and method of the independent claims.

As used herein, with 'Seebeck coefficient' is meant the ratio between the generated voltage and the temperature difference across that material.

As used herein, with 'Seebeck voltage' is meant the potential difference over one or more materials due to the Seebeck effect.

5 The structure according to the invention comprises:

- a substrate,

- a heater circuit part comprising a heater element, thermally isolated from the substrate except for at least a first heat conduction path for conducting heat from the heater element to the substrate, the first heat conduction path being
10 connected at a first connection point of the heater element and comprising the thin film material to be measured,

- a first measurement circuit part, comprising a first electrically conductive path from a first contact on the substrate to the first connection point and a second electrically conductive path from the first connection point to a second contact on
15 the substrate, the first measurement circuit part comprising a material having a Seebeck coefficient in a predetermined range in the first and/or second electrically conductive path, such that a DC voltage difference measured between the first and second contacts on the substrate is indicative of a temperature difference between the first connection point and the substrate.

20 As used herein, with "heater circuit part comprising a heater element, thermally isolated from the substrate except for at least a first heat conduction path for conducting heat from the heater element to the substrate, the first heat conduction path being connected at a first connection point of the heater element and comprising the thin film material to be measured" is meant that there are
25 connections to the heater element for applying a voltage, which connections are electrically but not necessarily thermally conducting. The heater circuit and the measurement circuit can use common paths or not.

As used herein, with "thermally isolated except for at least a first heat conduction path" is meant that there is one or more path which is optimized for
30 conducting heat to the substrate, but this does not exclude that there are other connections between the heater element and the substrate, e.g. electrically conducting paths. However the thermal conductance of these paths is minimized, such as is e.g. the case for the second electrically conductive path. In general one

could say that the thermal resistance of the non-heat-conducting paths is preferably at least 20 times higher than that of the heat-conduction paths.

An analysis of the prior art has shown that the temperature measurement in traditional TCR-based test structures is not very accurate, because of a non-constant temperature profile in the temperature monitor and the presence of a temperature-sensitive parasitic electrical resistance.

This problem is solved according to the invention, in that the first measurement circuit part comprises a first electrically conductive path from the first contact to the first connection point and a second electrically conductive path from the first connection point to the second contact on the substrate and furthermore comprises a material having a Seebeck coefficient in the first and/or second electrically conductive path. In this way the DC voltage difference measured between the first and second contacts on the substrate is indicative of a temperature difference between the first connection point and the substrate.

The Seebeck effect denotes that an electrical potential difference, named as Seebeck voltage, is created in the presence of a temperature difference across some materials. The Seebeck voltage between two points of such material is determined only by the net temperature difference at those points. Hence, in the structure of the present invention a local temperature measurement at the first connection point can be performed instead of an average measurement over the whole structure. Therefore a method based on the Seebeck effect can enhance the accuracy with respect to methods based on TCR..

Another advantage of the structure of the present invention is that the parasitic heat loss from the heater element to the substrate can be minimized, by thermally isolating the heater element from the substrate, except for at least a first heat conduction path.

Another advantage of the structure and method of the present invention is that (for most semi-conducting materials) a single structure is enough to determine the thermal conductivity of thin film material, thus there is no need for a differential measurement on a set of two or more structures.

Another advantage of the structure and method of the present invention is that it can be more widely applied than some prior art methods like the 3ω method, in particular to thin film materials which can be only a few micrometers thick. Due

to this wide applicability, the invention can be used to measure the thermal conductivity of thin film materials used in VLSI and MEMS fabrication.

Another advantage of the structure of the present invention is that it can be fabricated in a CMOS compatible manner. The thermal conductivity of thin film materials is highly dependent on process conditions, because the heat transport in thin films is to a large extent determined by various process-related factors, such as the stoichiometry, the crystalline structure, the grain size and the thermal history. Thus it is an advantage to fabricate the test structure and the devices on the same wafer. The co-fabricated test structure allows better data consistency and higher measurement accuracy, compared to the test structures fabricated separately.

In a preferred embodiment, the first electrically conductive path is a common part of the first measurement circuit part and of the heater circuit part. This means that the first electrically conductive path is used for current supply to the heater (along with another electrically conductive path) as well as for the measurement. Using conductive paths in common has the advantage of simplifying the structure and the measurement process.

In a preferred embodiment, the heater element is suspended above the substrate, to achieve the thermal isolation from the substrate. This can avoid the necessity of a thermally isolating substrate to minimize measurement errors due to the thermal losses through the substrate. This is an advantage in case of for example single crystalline silicon wafers widely used in VLSI and MEMS fabrication.

In a preferred embodiment, the substrate comprises an electrically insulating region on its surface, above which the heater element is located. This can avoid electrical shortcut via the substrate.

In a preferred embodiment, the first and second electrically conductive paths of the first measurement circuit part are suspended above the substrate. This can avoid the necessity of a thermally isolating substrate to minimize measurement errors due to the thermal losses through the substrate.

In a preferred embodiment, the first heat conduction path and the first electrically conductive path are formed on a short cantilever, and the second electrically conductive path is formed on a long cantilever.

In a preferred embodiment, at least part of the second electrically conductive path has a meandering shape. An advantage of a meandering shape as compared to a straight line, is that a long path and thus a high thermal resistance can be realised on a limited surface area. That way the heat loss via the second electrically conductive path becomes insignificant. Moreover, it is better withstanding mechanical stress.

In a preferred embodiment, the thermal resistance of the second electrically conductive path is at least 20 times, preferably 50 times higher than the thermal resistance of the first heat conduction path. In this way nearly all of the generated heat is conducted through the sample material, and this allows a more precise determination of thermal conductance.

In a preferred embodiment the structure further comprises: a second heat conduction path for conducting heat from the heater element to the substrate, the second heat conduction path being connected at a second connection point of the heater element and comprising the thin film material to be measured; a second measurement circuit part comprising a third electrically conductive path from a third contact on the substrate to the second connection point on the heater element and a fourth electrically conductive path from the second connection point to a fourth contact on the substrate, the second measurement circuit part comprising the same materials as the first measurement circuit part, i.e. having the material with a Seebeck coefficient in the predetermined range in the third and/or fourth electrically conductive path.

This embodiment of the structure is preferably symmetrical, so that the calculations are simplified, and this also offers the possibility for measuring the voltage V_2 at two locations. If the two measured values deviate too much, errors in the design or defects in the structure can be detected. When the values are similar, they can be averaged to get a more accurate result.

In a preferred embodiment, the predetermined range of the Seebeck coefficient is a value higher than $50 \mu\text{V/K}$ in absolute value. This results in a large value for V_2 , i.e. a large signal, which can be measured accurately.

In a preferred embodiment, the first heat conduction path is made of the same material as the heater element. In this way the ratio of the parasitic electrical resistance to the heater resistance is temperature independent, and its effect can be more easily taken into account.

In a preferred embodiment, the heat conduction path is made of the same material as the heater element, having an electrical resistivity between 10 mΩ.cm and 100 mΩ.cm. When using such material for the heater element a simpler process can be used, and a more accurate result can be achieved.

5 In a preferred embodiment the first electrically conductive path and the second electrically conductive path are made of semi-conducting materials with opposite doping type. In that case the Seebeck voltages of both paths are adding up instead of cancelling out realising a larger Seebeck voltage V_2 , i.e. a larger signal, which can be measured more accurately.

10 The present invention also discloses a method for determining the thermal conductivity of a thin film material by means of the structure described above, the method comprising the steps of: a) determining the Seebeck coefficients of the materials of the first and second electrically conductive paths; b) applying an AC voltage over the heater circuit part; while measuring the current through the heater
15 circuit part; c) measuring the DC voltage difference between the first and second contacts on the substrate; d) determining the thermal conductivity of the thin film material, using the Seebeck coefficients determined in step (a), using the injected power determined from the values of the voltage and current of step (b), and using the measured DC voltage difference (V_2) of step (c).

20 An advantage of this method is that all parameters, especially the DC voltage V_2 , can be measured or determined very accurately, thus achieving a very accurate result for the temperature, and hence also for the thermal conductivity.

The present invention also discloses a method for determining the thermal conductivity of thin film insulator material, by performing a differential
25 measurement according to the method described above, on two test structures, one with and one without the thin film material to be measured deposited on top of at least the first heat conduction path. This way the method also works for material which is not electrically conducting.

30 **Brief description of the drawings**

The invention will be further elucidated by means of the following description and the appended drawings.

Figure 1: schematic designs of thin film test structure for determination of thermal conductivity (test structure is not drawn to the scale) (a) test structure with one long cantilever; (b) test structure with two long cantilevers.

Figure 2: (a) cross sections of the test structures illustrating the point where the "short" and the "long" cantilever are overlapping ; (b) top view of the test structure represented in Fig. 1(b) for the determination of thermal conductivity.

Figure 3: a finite element model for the designed test structure.

Figure 4: a simulated temperature difference with respect to the substrate due to Joule heating (a) on the test structure; (b) across the p-type SiGe cantilever.

Figure 5: a calibration curve between the temperature difference across SiGe sample and the temperature difference measured with a commercial thermocouple for reference.

Figure 6: a measurement curve for the Seebeck coefficient of the p-type and the n-type SiGe as a function of temperature

Figure 7: a schematic of the process flow for the designed test structure (test structures are not drawn to the scale).

Figure 8: a SEM picture of the designed test structure after HF release.

Figure 9: a measured Seebeck voltage V_2 as a function of input voltage V_1 for a specific test structure.

Figure 10: a graph with values for the thermal conductivity of p-type SiGe measured on a variety of designed test structures.

Figure 11: a schematic design of another embodiment of a thin film test structure, according to the invention.

Modes for carrying out the invention

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and

the relative dimensions do not necessarily correspond to actual reductions to practice of the invention.

Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. The terms are
5 interchangeable under appropriate circumstances and the embodiments of the invention can operate in other sequences than described or illustrated herein.

Moreover, the terms top, bottom, over, under and the like in the description and the claims are used for descriptive purposes and not necessarily for
10 describing relative positions. The terms so used are interchangeable under appropriate circumstances and the embodiments of the invention described herein can operate in other orientations than described or illustrated herein.

The term "comprising", used in the claims, should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements
15 or steps. It needs to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression "a device comprising means A and B" should not be limited to devices consisting only of components A and B.
20 It means that with respect to the present invention, the only relevant components of the device are A and B.

The preferred embodiment of the current invention described below presents a micromachined test structure made by CMOS compatible processes for measuring the thermal conductivity of thin films. The measurement principle is
25 based on the Seebeck effect.

The Seebeck effect denotes that an electrical potential difference, named as Seebeck voltage, is created in the presence of a temperature difference across a metal or a semiconductor material. The ratio between the Seebeck voltage and the temperature difference is defined as the Seebeck coefficient. The Seebeck
30 voltage is determined only by the net temperature difference across the sample material and is independent of the particular temperature profile. Therefore Seebeck-effect based temperature sensing can be accurate.

A test structure is presented to measure thermal conductivity of thin film materials based on the Seebeck effect. Furthermore, a method for the fabrication

of the test structure and a method for measuring the thermal conductivity with the test structure are presented. The test structure is fabricated by surface micromachining technology without for example KOH bulk etching involved. Consequently, its fabrication process is compatible with those for VLSI circuits and
5 MEMS devices.

For sample materials having a relatively large Seebeck coefficient, such as lightly doped poly-Si and lightly doped poly-SiGe, the heater, the temperature sensor and the sample material can be merged together by using the same material, resulting in a relatively simple structure and a relatively easy fabrication
10 process.

For sample materials having a relatively small Seebeck coefficient, such as heavily doped poly-Si and heavily doped poly-SiGe, the thermal conductivity can be determined with the designed test structure by fabricating the long cantilevers out of a material with a large Seebeck coefficient. Thus the temperature sensing
15 can be implemented, The test structure can be made relatively simple and differential measurements are not necessary.

Beyond semiconductor materials, such as poly-Si and poly-SiGe, metals and insulators can be measured with the designed test structure as well by implementing a differential measurement on two sets of test structure, i.e. one
20 without and one with the sample material deposited on top of the "short" cantilevers.

In the specific example given hereafter, the test structure is made of p-type and n-type poly-Si_{70%}Ge_{30%} deposited by LPCVD. Also other materials, such as poly-Si and gallium arsenide (GaAs) can be measured in the same way.

25 Schematic representations of the test structure fabricated on a substrate (1) covered with an electrically insulating material (6) (for example a Si substrate covered with Si₃N₄) are shown in Figure 1. The insulating layer (6) can be omitted in case the substrate is electrically insulating as such.

On a substrate (1) with electrically insulating top surface (6), two "short"
30 cantilevers (2) are anchored at one end (points "A" and "B" in Figure 1(a)).

Both "short" cantilevers (2) are made of the same material(s). The "short" cantilevers should be electrically conducting or semiconducting, but they cannot be electrically insulating. They can be doped semiconductors. The electrical

resistivity of the "short" cantilevers preferably varies between 1 mΩ.cm and 1000 mΩ.cm, or even better between 10 mΩ.cm and 100 mΩ.cm.

The "short" cantilevers (2) can be made of only the material, of which the thermal conductivity needs to be measured. If this material does not have the electrical resistivity specified above, the thin film of which the thermal conductivity needs to be measured can be deposited on top of supporting "short" cantilevers made of a material with the required electrical properties. In the latter case, a differential measurement is done, i.e. the voltage realized on an uncovered cantilever is compared to the voltage realized when the cantilever is covered with the thin film. In principle, this test structure can be used to measure the thermal conductivity of any thin film material. If the material of the "short" cantilevers has a Seebeck coefficient, its value has to be known. As this value is also dependent on process parameters, it is better to measure this value.

The dimensions of the "short" cantilever (2) can for example be the following: The thickness (t_p) of the cantilever can vary between 100 nm and 5000 nm or even better between 500 nm and 2000 nm. Parallel to the plane of the substrate, the length (L_{p1}) and the width (W_{p1}) of the cantilever can vary between 1 μm and 1mm, or between 5 μm and 500 μm, or between 10 μm and 100 μm. The shape can be square, rectangular, triangular, or any other shape can be used. Materials that can be used for the "short" cantilevers (2) are for example poly-Si, poly-SiGe, GaAs, GaN, and BiTe,..... But any other material fulfilling the above-mentioned requirements can be used.

The "short" cantilevers (2) are connected with a suspended thin beam (3) at the other end (points "C" and "D" in Figure 1), being a resistor or a heater. An AC (V1) voltage applied to the resistor will result in a heat flow due to the Joule heating in the heater. The waveform of this AC voltage can be square, sinusoidal, or any other shape can be used.

To realize a large enough temperature rise, the heater is preferably made of an electrically conductive material with an electrical resistivity higher than 1 mΩ.cm or higher than 10 mΩ.cm, or with an electrical resistivity varying between 1 mΩ.cm and 1000 mΩ.cm, or even better between 10 mΩ.cm and 100 mΩ.cm. If the thin film material under test has an electrical resistivity in the ranges specified above, the heater can be made of it. Otherwise a different material must be used, e.g. the

same material supporting the “short” cantilevers. Materials that can be selected for the beam (3) are for example poly-Si, poly-SiGe, GaAs, GaN, and BiTe,..... But any other material fulfilling the above-mentioned requirements can be used.

Similarly, at least one “long” cantilever (4) is anchored on the substrate (point “E” in Figure 1). At the other end (point “C” in Figure 1) the “long” cantilever (4) is overlapped with one of the “short” cantilevers (2). Figure 1(a) represents the case with only one “long” cantilever. Also two “long” cantilevers (4) can be anchored on the substrate (1) at one end (points “E” and “F” in Figure 1(b)). In that case, at the other end (points “C” and “D” in Figure 1) these two cantilevers (4) are overlapped with the “short” cantilevers (2). Different from the “short” cantilevers, the “long” cantilevers are structurally separate from each other and are only connected by the heater. In Figure 2(a) a cross section of the structure is represented illustrating the overlap of the “short” and the “long” cantilever. In Figure 2(b) a top view is given of the structure represented in Figure 1(b).

It may be advantageous to make the short cantilever and the long cantilever from materials with opposite doping type. In that case the Seebeck voltages in the two cantilevers (of the overlapping short and long cantilever) are adding up instead of cancelling out realising a larger Seebeck voltage (“V2”), i.e. a larger signal.

The “long” cantilevers should be electrically conducting or semiconducting, but they cannot be electrically insulating. They can be doped semiconductors. The electrical resistivity of these cantilevers is preferably equal to or lower than 1000 mΩ.cm or between 1 and 1000 mΩ.cm.

To measure the thermal conductivity by means of the Seebeck effect, the “long” cantilevers (4) preferably have a thermal resistance that is higher or even better, much higher than the thermal resistance of the “short” cantilevers (2). Preferably the thermal resistance of the “long” cantilevers is more than 20 times higher or even better 50 times higher or 100 times higher than the thermal resistance of the “short” cantilevers. The length (L_n) and the width (W_n) of the “long” cantilever can be tuned to achieve this. An interesting geometrical shape is a meandering shape, whereby the meandering cantilever is much longer and narrower than the “short” cantilevers. An advantage of a meander shape as compared to a straight line, is that it is better withstanding mechanical stress.

Furthermore a long path and thus a larger thermal resistance can be realised on a limited surface area.

The dimensions of the meanders can for example be chosen as follows. The thickness (t_n) can vary between 100 nm and 5000 nm. The effective length
5 (L_n) of the meanders can for example vary between 10 μm to 1000 μm . The width of the meanders (W_n) can vary between 1 μm and 100 μm .

To realize a measurable Seebeck voltage, the absolute value of the Seebeck coefficient of the material of the "long" cantilevers is preferably equal to or higher than 50 $\mu\text{V/K}$ or higher than 100 $\mu\text{V/K}$. The absolute value of the
10 Seebeck coefficient of the "long" cantilevers is preferably in the range between 50 $\mu\text{V/K}$ and 300 $\mu\text{V/K}$, or between 100 $\mu\text{V/K}$ and 1000 $\mu\text{V/K}$ or between 50 $\mu\text{V/K}$ and 1000 $\mu\text{V/K}$, or between 100 $\mu\text{V/K}$ and 300 $\mu\text{V/K}$.

Conducting pads, preferably metal pads (5) (see Figure 1(b)) can be made at points "C" and "D" for electrical interconnection between the short and long
15 cantilevers as well as on top of the anchoring points (A), (B), (E), (F) for electrical measurement. These metal pads can for example be made of Al, Cu,

To realize a temperature difference between point "C" and points "A" or "E", an AC voltage is applied on the electrical resistor between points "A" and "B". This temperature difference will result in a Seebeck voltage ("V2") between points "A"
20 and "E" (or else "B" and "F"). From the Seebeck voltage, the temperature difference between point "C" and points "A" or "E" can be determined. As the thermal resistance of the meander between points "C" and "E" (or points "D" and "F") is much higher than the thermal resistance between points "C" and "A" (or "D" and "B"), most of the generated heat flows through the "short" cantilevers (2) into
25 the substrate. The generated heat can be calculated from the injected AC voltage "V1" and the measured electrical resistance between points "A" and "B", or from the injected AC voltage "V1" and the current "I" which is measured simultaneously. Thus, from the measured DC voltage difference "V2", indicative for the temperature difference, and from the calculated generated heat, the thermal
30 resistance of the "short" cantilevers for example between points C and A can be determined. Furthermore, the geometries of the "short" cantilevers are known by design or can be measured. Thus the thermal conductivity of the material of the "short" cantilever can be determined.

The contacting regions (A), (B), (E), (F) can have a width and length varying between 10 μm and 5000 μm , or between 20 μm and 1000 μm , 50 μm and 500 μm or between 80 μm and 200 μm . The contacting regions can have a square shape, rectangular shape, oval shape, but any other shape can be used.

5 The test structure can be fabricated with for example thin film surface micromachining technology. An example of a process flow is shown in Figure 7. Either an electrically insulating substrate can be taken or an electrically insulating layer or region (6) can be provided on a substrate (1) for electrical isolation. Then a layer (7), which can be selectively removed against the structural materials for
10 the “short” cantilever, the “long” cantilever and the metal pads, can be deposited, e.g. by chemical vapour deposition, and patterned, e.g. by photolithography and wet etching technique, to form the sacrificial layer (Figure 7(a)). Then the layer (2) to be measured can be deposited and patterned (Figure 7(b)), such as to realise the “short” cantilever (2) and preferably also the heater element (3). Then the
15 material (4) preferably with a large Seebeck coefficient in the opposite sign to that of the material for the “short” cantilever can be deposited and patterned such as to realise the “long” cantilever (Figure 7(c)). To interconnect the “short” and “long” cantilevers (2) and (4), a conducting material, preferably metal layer (5) can be deposited and patterned (Figure 7(d)). The deposition and the patterning of the
20 materials for the “short” cantilever, the “long” cantilever and the metal pads can be implemented with, but not limited to, the thin film surface micromachining techniques, such as chemical vapor deposition, sputtering, photolithography and etching. Finally, the test structure can be released by removing the sacrificial layer underneath the cantilevers selectively without damaging the test structure (Figure
25 7(e)).

 The structure can be measured as follows. First, the Seebeck coefficients of the “short” and the “long” cantilever materials are measured separately, e.g. with the method detailed in the example section below. The Seebeck coefficients are measured on the same materials as the test structure for thermal conductivity. The
30 geometries of the “short” cantilever(s), including the width, the length and the thickness, are measured either with microscope or scanning electron microscopy (SEM). The electrical resistance between metal pads (A) and (B) is measured, e.g. by using standard semiconductor parametric analyzer. Then the thermal measurement is conducted in a vacuum chamber to minimize the thermal loss. An

AC voltage "V1" is applied between metal pads (A) and (B), e.g. with a function generator, and meanwhile the DC voltage "V2" between metal pads (A) and (E) or (B) and (F) is measured, e.g. with a digital voltage multimeter. Finally the thermal conductivity of the "short" cantilever material is calculated from the measurement results.

Example 1

A specific example is the following: Two "short" cantilevers (2) made of p-type thin films are anchored on Si₃N₄-coated Si substrate at one end (point "A" and "B" in Figure 1) and connected with a thin beam (3) also made of p-type thin film at the other end (points "C" and "D" in Figure 1). Similarly, two "long" cantilevers (4) made of n-type thin films are also anchored on the substrate at one end (points "E" and "F" in Figure 1) and are overlapped with p-type cantilevers at the other end (points "C" and "D" in Figure 1).

Different from the p-type "short" cantilevers, the n-type "long" cantilevers are structurally separate from each other and only connected by the thin beam (between points "C" and "D" in Figure 1). Moreover, n-type cantilevers, which can be made in a meandering shape, are typically much longer and narrower than the p-type cantilevers. Metal pads are made at the p-n junctions (at points "C" and "D") for electrical interconnection as well as on top of the anchors ("A", "B", "E", "F") for electrical measurement.

For example (see Figure 2(b)), the "long" cantilever (4) can be made of n-type SiGe material. The Seebeck coefficient of the "long" cantilever (α_n) can be -190 $\mu\text{V/K}$ and the electrical resistivity can be 6.2 m Ωcm . The "long" cantilever can have a meander shape with for example the following dimensions: an effective length (L_n) of 230 μm , a width (W_n) of 4~10 μm , and a thickness (t_n) of 1 μm . The thermal resistivity can be ~3.5 W/m/K.

The "short" cantilever and beam can be made of p-type SiGe material with for example a Seebeck coefficient (α_p) of 35 $\mu\text{V/K}$ and an electrical resistivity of 1.1 m Ωcm . The thermal resistivity can be ~3.5 W/m/K. The short cantilever (2) can have a rectangular shape with for example the following dimensions: 40 μm long (L_{p1}), 30 μm wide (W_{p1}) and 1 μm thick (t_{p1}). The beam can be shaped as a thin

long stripe with for example the following dimensions: 120 μm long (L_{p2}), 4~10 μm wide (W_{p2}) and 1 μm thick (t_{p2})

The measurement of the thermal conductivity of the p-type material is based on the Seebeck coefficients of both p-type and n-type poly-SiGe. The measurement of these Seebeck coefficients is described below. The measurement of thermal conductivity must be performed in a vacuum chamber to reduce the thermal loss through air convection and/or conduction to the ambient. An AC square voltage (" V_1 " in Figure 1) can be injected between the two metal pads of p-type SiGe cantilevers (point "A" and "B"). Because the beam (3) between "C" and "D" is much thinner and longer than the two cantilevers (2), most of the heat is generated between these two points, namely along the p-type heater. From the measured current " I " between "A" and "B", the generated heat can be obtained as:

$$Q = V_1 I \quad (1)$$

where Q is the generated heat and " I " is the current between "A" and "B". Because the n-type SiGe "long" cantilever is much longer and narrower than the p-type SiGe "short" cantilever, the thermal resistance of the n-type SiGe cantilever can be assumed to be much higher (i.e. at least 50 times higher depending on the dimensions) than that of the p-type SiGe "short" cantilever. Therefore, it can be assumed that most of the generated heat flows through the p-type SiGe "short" cantilevers into the substrate, which behaves as a heat sink. Moreover, due to the structural symmetry, the heat flowing through both p-type SiGe cantilevers is essentially the same. Consequently, the temperature at point "C" and "D" also is essentially the same. Furthermore, a temperature difference ΔT is meanwhile established between point "C" or "D" and the silicon substrate. This temperature difference ΔT can be determined by measuring the resulting Seebeck voltage (" V_2 " in Figure 1) either between "A" and "E" or between "B" and "F":

$$\Delta T = \frac{V_2}{\alpha_p + \alpha_n} \quad (2)$$

where α_p and α_n are the Seebeck coefficients for p-type and n-type SiGe respectively. Although V_1 is partially superimposed to V_2 , V_2 , which is a DC

voltage, can be measured accurately without interference from V_1 , which is a squarewave AC voltage.

Given Q and ΔT , the total thermal resistance of the suspending structure is determined by:

5

$$R_{th} = \frac{\Delta T}{Q} \quad (3).$$

On the other hand, the thermal resistance of the p-type “short” cantilevers is determined by their dimensions and the thermal conductivity of p-type SiGe. A typical mask layout for the designed test structure is depicted in Figure 2. The p-type SiGe structure consists of two cantilevers (2) and one beam (3), which are connected electrically in series. The cantilever has a length of L_{p1} and a width of W_{p1} . The beam has a length of L_{p2} and a width of W_{p2} . As shown also in Figure 2, the n-type cantilever has a length of L_n and a width of W_n .

15 The total thermal resistance of the p-type “short” cantilever R_{th} is composed of two parts: the 1D thermal resistance R_{th_1D} and the spreading thermal resistance R_{th_s} . The expressions of R_{th_1D} and R_{th_s} are well known in the literature [M. M. Yovanovich, Y. S. Muzychka and J. R. Culham, “Spreading resistance of isoflux rectangles and strips on compound flux channels”, *Journal of Thermophysics and*
20 *Heat Transfer*, Vol. 13, No. 4, Oct. 1999] then it is possible to write

$$R_{th} = R_{th_1D} + R_{th_s} = \frac{1}{k_p} \left[\frac{L_{p1}}{W_{p1}} + \frac{1}{\pi^3 \left(\frac{W_{p2}}{W_{p1}} \right)^2} \sum_{n=1}^{\infty} \frac{\sin^2 \left(n\pi \frac{W_{p2}}{W_{p1}} \right)}{n^3} \right] \quad (4).$$

It can be seen that R_{th} is inversely proportional to the thermal conductivity of p-type poly-SiGe k_p according to a factor determined by the structure dimensions.

25 Thus Equation (4) reduces to:

$$R_{th} = \frac{c}{k_p} \quad (5)$$

where c is the term that is independent of k_p in Equation (4). Thus from Equation (1) - (5), the expression for the thermal conductivity k_p of p-type SiGe is attained as:

$$k_p = c \cdot \frac{\alpha_p + \alpha_n R}{R} \cdot \frac{V_1^2}{V_2} \quad (6).$$

In Equation (4) only the thermal resistance of p-type SiGe cantilever is considered for simplification. Because the thermal resistance of the n-type SiGe cantilevers is much larger than that of the p-type SiGe cantilevers, the thermal resistance of the whole suspending structure is basically determined by the p-type SiGe cantilevers. Below, the heat loss through the n-type SiGe cantilevers is included in the data processing to improve the measurement accuracy.

Similarly, the thermal conductivity of n-type SiGe k_n can be measured by using the test structure wherein the p-type and the n-type SiGe materials are switched over as opposed to the scheme shown in Figure 1.

Metal interconnect ("5" in Figure 2(a)) is used to electrically bridge the p-type SiGe and the n-SiGe cantilevers with Ohmic contact at point "C" and "D". In the present design, aluminum is used to form Ohmic contacts with both the p-type and the n-type SiGe. The n-type SiGe cantilevers are made in a meandering shape in an attempt to alleviate the adverse effect of residual stress and meanwhile reduce the needed chip area.

The functioning of the designed test structure is based on three assumptions: 1) the analytical modelling can be used to precisely calculate the thermal resistance of the p-type SiGe cantilevers; 2) most of the heat is generated along the heater between point "C" and "D" under a certain applied voltage or current; 3) most of the generated heat flows through the p-type SiGe cantilevers into the substrate. These three assumptions were verified by using both analytical modelling and finite element modelling.

As described above, the modelling of the thermal resistance of p-type "short" SiGe cantilevers is essential to the precise determination of the thermal conductivity of p-type SiGe material. Because the value of the spreading thermal resistance can be as large as the 1D thermal resistance depending on the exact structural dimensions, an omission of the spreading thermal resistance can induce a measurement error as large as 100%. With 1D is meant "one dimensional".

The 1D thermal resistance can be calculated easily. A set of the typical dimensions for the designed structure includes $30\text{ }\mu\text{m}$ for L_{p1} , $40\text{ }\mu\text{m}$ for W_{p1} , $1\text{ }\mu\text{m}$ for t_{p1} . Assumed that k_p is 3 W/m/K , R_{th_1D} is $2.5\times 10^5\text{ K/W}$. The calculation of the spreading thermal resistance can be done [M. M. Yovanovich, Y. S. Muzychka and J. R. Culham, "Spreading resistance of isoflux rectangles and strips on compound flux channels", *Journal of Thermophysics and Heat Transfer*, Vol. 13, No. 4, Oct. 1999]. The width of the heat source, which is the same as the width of the p-type SiGe heater, can be taken as $4\text{ }\mu\text{m}$, for instance. Thus the spreading thermal resistance R_{th_s} is $2.088\times 10^5\text{ K/W}$ and the total thermal resistance R_{th} is $4.588\times 10^5\text{ K/W}$.

The finite element model for the designed test structure is built with the same dimensions used for the analytical modelling, as shown in Figure 3. Due to the structural symmetry, only half of the test structure is constructed for simplification. Poly-SiGe is introduced into this model with an assumed thermal conductivity of 3 W/m/K and other material properties are drawn from experiments.

In the model (see Figure 3), the "short" cantilever (2) and beam (3) are made of p-type poly-SiGe, the "long" cantilever is made of n-type poly-SiGe. The pads "A" and "E" are made with poly-SiGe and then covered with Al. Al pad "A" is kept at a fixed electrical potential and at a fixed temperature. Al pad "E" is kept at the same fixed temperature as Al pad "A". A fixed current flux is introduced into the beam (3).

From this finite element model (FEM), a coupled analysis of the electrical and thermal domain can be done. The boundary conditions are: fixed current flux at the middle plane of the heater, fixed electrical potential at the bottom surface of the anchor for the "short" cantilever and fixed temperature at the bottom surfaces of the anchors for both the "short" and the "long" cantilevers, as shown in Figure 3. Thus, in this simulation, an electrical current of 0.5 mA flows through the heater and the p-type SiGe cantilever into the anchor.

The simulated temperature difference with respect to the substrate due to the Joule heating of this current is shown in Figure 4. The temperature decreases along the SiGe heater (3) from the center to the end (Figure 4(a)). A zoom-in at the "short" p-type SiGe cantilever (2) reveals that the isothermal surface does not coincide with the cross-sectional plane of the p-type SiGe cantilever (Figure 4(b)), which is the origin of the spreading thermal resistance. Because the electrical

resistance of the heater (between points "A" and "B") is $170\ \Omega$, the generated heat due to Joule heating is $42.5\ \mu\text{W}$. From the FEM, the overall temperature difference over the short cantilevers is $18.66\ ^\circ\text{C}$. If all the generated heat is assumed to flow through the p-type SiGe cantilever, the total thermal resistance R_{th} from FEM is thus $4.391 \times 10^5\ \text{K/W}$, which is only 4.5% lower than the value from the analytical modelling. If the heat loss through the n-type SiGe cantilever, which is normally several percent of the total heat flow, is taken into consideration, the result from FEM is even closer to that from the analytical modelling. This consistency confirms the validity of the analytical solution to the total thermal resistance of the p-type SiGe cantilever.

The second and the third assumptions mentioned before can be validated by analytical modelling and FEM. As to the Joule heating, because the electrical resistance of the heater is 20 times larger than that of the two "short" cantilevers combined together in series, 95.24% of the heat is generated within the heater element while only 4.76% of the heat is generated in the "short" cantilevers. With regard to the distribution of the generated heat, because the thermal resistance of the "long" cantilever is more than 40 times larger than that of the "short" cantilever, 97.6% of the generated heat flows through the "short" cantilever into Si substrate and only 2.4% of the generated heat flows through the "long" cantilever into the Si substrate.

The fabrication of the designed test structure is based on surface micromachining technology. The process flow is depicted in Figure 7. A silicon substrate (1) was covered with a 200-nm-thick Si_3N_4 layer (6) for electrical isolation. Then a $1.2\text{-}\mu\text{m}$ -thick SiO_2 layer (7) was deposited by plasma enhanced chemical vapor deposition (PECVD) at $700\ ^\circ\text{C}$ and then patterned with BHF to form the sacrificial layer (Figure 7(a)).

The $1.0\text{-}\mu\text{m}$ -thick p-type SiGe layer (2, 3) was deposited by low pressure chemical vapor deposition (LPCVD) and patterned by using reactive ion etching (RIE) (Figure 7(b)), such as to realise the "short" p-type SiGe cantilever (2) and the heater (3).

Then the n-type SiGe layer (4) is deposited and patterned such as to realise the "long" n-type SiGe cantilever (Figure 7(c)). To interconnect the p-type and the n-type SiGe, aluminium (5) was sputtered and patterned by wet etching (Figure

7(d)). Finally, the test structure was released in the mixture of glycerol and BHF with stirring, thereby removing the SiO_2 layer underneath the cantilevers, and then dried in critical point dryer (Figure 7(e)).

The structure of the released test structure was analyzed under Scanning
5 Electron Microscopy (SEM). As shown in Figure 8, the p-type and n-type SiGe cantilevers are fully released.

Because an estimate of the Seebeck coefficient is necessary for the implementation of the designed test structure, it needs to be measured in advance. An experimental set-up, where a temperature difference can be imposed
10 across a macroscopic poly-SiGe sample and meanwhile the resulted Seebeck voltage can be measured, has been employed for this purposed. The Seebeck coefficient for the n-type SiGe of this example ranges from $-185 \mu\text{V/K}$ to $-190 \mu\text{V/K}$ for a temperature difference up to around 16 K. Similarly, the Seebeck coefficient for the p-type SiGe of this example ranges from $35 \mu\text{V/K}$ to $40 \mu\text{V/K}$.

15 The test structure was measured in a vacuum to reduce the thermal loss through air convection and/or conduction. In the experiment, a function generator was then used to apply the AC voltage " V_1 " across the p-type SiGe heater. Meanwhile, a multimeter was used to measure the resulting Seebeck voltage V_2 .

The measurement result on a certain test structure is shown in Figure 9. In
20 this experiment, V_1 was increased from 50 mV to 400 mV in steps of 50 mV and meanwhile V_2 was measured for each value of V_1 . The value of V_2 is taken once the temperature difference is stabilized. From Figure 9, the linear relationship between V_1^2 and V_2 is clearly observed. The slope of the fitted straight line, combined with the structural dimensions, the Seebeck coefficients and the
25 electrical resistance, can be used in the calculation of the thermal conductivity by using Equation (6).

In Equation (8), R is the electrical resistance of the heater, which can not be measured directly between points C and D due to the small size of suspending metal pads. Only the electrical resistance between point "A" and "B", namely the
30 sum of the electrical resistances of the p-type SiGe cantilevers (2) and the heater (3), can be measured directly with HP4156 probe station. But the electrical resistance of the heater can be derived from the overall electrical resistance through calculations based on the structural dimensions. For instance, the ratio

between the heater electrical resistance and the overall electrical resistance can be given by:

$$c_1 = \frac{L_{p2}/W_{p2}}{2L_{p1}/W_{p1} + L_{p2}/W_{p2}} \quad (9)$$

5

where c_1 is the correction factor for the electrical resistance.

Another correction comes from the thermal loss through the n-type SiGe cantilevers, although it is minimal compared with the heat flow through the p-type SiGe cantilevers. Similar with the correction factor for electrical resistance, the correction factor for thermal resistance c_2 can also be derived from the structural dimensions as:

10

$$c_2 = \frac{L_n/W_n}{L_{p1}/W_{p1} + L_n/W_n} \quad (10).$$

15

With the corrections for the electrical resistance and the thermal resistance considered, Equation (8) for the expression of the thermal conductivity is then given by:

$$k_p = c \cdot \frac{R}{\alpha_p + \alpha_n} \cdot \frac{V_2}{V_1^2} \cdot \frac{1}{c_1 c_2} \quad (11).$$

20

After the corrections for the electrical resistance and the thermal resistance, the thermal conductivity of the measured structure was calculated to be about 3.5 W/m/K.

The same measurement was performed on a number of test structures with different length of the p-type SiGe cantilevers. The measurement results are shown in Figure 10.

25

As shown in Figure 10, the mean values (indicated by the symbols “ Δ ”) of k_p measured on various test structures tend to converge towards about 3.5 W/m/K, which is consistent with values reported in literature [10]. This convergence demonstrates the functionality of the designed test structure and the absence of systematic errors related to structural dimensions. Although some scattering is observed, it can be largely minimized. The scattering is firstly attributed to the

30

non-uniformity associated with the fabrication process. The variation in the thicknesses of various layers is estimated to be about 5~10% within an 8-inch Si wafer. Similarly, the Seebeck coefficients of poly-Si_{70%}Ge_{30%} layers also slightly vary due to processing non-uniformity. The influence of process non-uniformity can be minimized by optimizing processing parameters and performing individual thickness measurement for each test structure. Moreover, the electrical resistance of the test structure is actually coupled to the temperature as well, especially for materials having a large TCR. This issue can be addressed by a more comprehensive data analysis, in which the change of the electrical resistance due to the Joule heating is taken into consideration.

Both the modelling and the experimental results show that the designed test structure for thermal conductivity is an advantageous approach for the measurement of thermal conductivity for thin film materials. Different from most of the traditional test structures and test methods, the proposed test structure and method is based on the Seebeck effect to determine the temperature difference. Compared with other test structures, it offers several advantages, such as compatibility with CMOS technology, simple fabrication and easy implementation.

Although only the measurement results obtained on the poly-SiGe are presented, this approach can be easily extended to other semiconductor materials with a relatively high Seebeck coefficient, such as poly-Si and BiTe.

Furthermore, by using the differential scheme, other thin film materials with only a limited Seebeck coefficient, such as Al, can also be measured. For example, Al can be deposited and patterned on top of the SiGe cantilevers. The thermal conductivity of Al can be obtained by comparing the measured value from test structure with Al and that from one without Al.

Example 2

Figure 11(a) shows another embodiment of the present invention, although most aspects are similar to the structure and method of the first example. The four short cantilevers are identical in size, and they are made of the thin film material to be measured. The heater circuit part is situated between contact "A" and contact "D", over which an AC voltage V1 will be applied. The heater element is situated between the points "E" and "F" and between the points "F" and "G", and is made

of the thin film material to be measured, and is suspended above the substrate. There are four heat conducting paths ("E-A", "F-B", "F-C", "G-D"), each conducting approximately 25% of the generated heat to the substrate. Note that this is only approximately true, as there is no heat generated in the path "B-F" and "C-F", but
5 by choosing the geometry of the structure such that the electrical resistance of "A-E" and "D-G" is much smaller than the electrical resistance of "E-F" and "F-G", the heat generated in "A-E" and "G-D" can be minimized. As in example 1, a correction factor can be derived to compensate for this.

The measurement circuit part is situated between contact "B" (or "C") and
10 contact "H", over which the Seebeck voltage V_2 is to be measured. It comprises the thin film material to be measured in path "B-F" and another material in the path "F-H". At least one of these materials has a Seebeck coefficient higher than 50 $\mu\text{V/K}$ in absolute value. The geometrical parameters (e.g length, width, thickness) of the long cantilever "F-H" are chosen such that the thermal resistance of the long
15 cantilever is at least 20, preferably 50 times higher than the thermal resistance of the short cantilevers. The voltage V_2 is indicative for the temperature difference between point "F" and the substrate. Approximately the same temperature difference can be measured between points "E" or "G" and the substrate, as explained above.

20 This design is basically a more complicated variant from the one shown in Figure 1(a) by connecting two heater elements to the same long cantilever. This embodiment shows however that it is not necessary to have a common part between the heater circuit part and the measurement circuit part.

Figure 11(b) shows the same structure as figure 11(a), but the
25 measurement is carried out differently. Now the AC voltage V_1' is applied between the points "A" and "B", and between the points "C" and "D", whereby the polarity is chosen such that the contacts "B" and "C" are kept at the same potential, and the contacts "A" and "D" are kept at the same potential. By doing this, the paths "B-F" and "C-F" do participate in the heat generation, and a similar correction factor c_1
30 can be calculated as for example 1

Claims

1. A structure for determining the thermal conductivity of a thin film material, comprising:

5 - a substrate (1),
 - a heater circuit part comprising a heater element (3), thermally isolated from the substrate except for at least a first heat conduction path (CA) for conducting heat from the heater element to the substrate, the first heat conduction path being connected at a first connection point (C) of the heater element and
10 comprising the thin film material to be measured,

 - a first measurement circuit part, comprising a first electrically conductive path (AC) from a first contact (A) on the substrate to the first connection point (C) and a second electrically conductive path (CE) from the first connection point (C) to a second contact (E) on the substrate, the first measurement circuit part
15 comprising a material having a Seebeck coefficient in a predetermined range in the first and/or second electrically conductive path (AC, CE), such that a DC voltage difference (V2) measured between the first and second contacts (A, E) on the substrate is indicative of a temperature difference between the first connection point (C) and the substrate.

20 2. A structure according to claim 1, wherein the first electrically conductive path (AC) is a common part of the first measurement circuit part and of the heater circuit part.

 3. A structure according to claim 1 or 2, wherein the heater element (3) is suspended above the substrate (1) to achieve the thermal isolation from the
25 substrate.

 4. A structure according to any one of the claims 1-3, wherein the substrate (1) comprises an electrically insulating region (6) on its surface, above which the heater element (3) is located.

 5. A structure according to any one of the previous claims, wherein the first
30 and second electrically conductive paths (AC, CE) of the first measurement circuit part are suspended above the substrate (1).

 6. A structure according to any one of the previous claims, wherein the first heat conduction path (CA) and the first electrically conductive path (AC) are

formed on a short cantilever (2), and the second electrically conductive path (CE) is formed on a long cantilever (4).

7. A structure according to any one of the previous claims, wherein at least part of the second electrically conductive path (CE) has a meandering shape.

5 8. A structure according to any one of the previous claims, wherein the thermal resistance of the second electrically conductive path (CE) is at least 20 times higher than the thermal resistance of the first heat conduction path (CA).

9. A structure according to any one of the previous claims, wherein the thermal resistance of the second electrically conductive path (CE) is at least 50
10 times higher than the thermal resistance of the first heat conduction path (CA).

10. A structure according to any one of the previous claims, wherein the structure further comprises

- a second heat conduction path (DB) for conducting heat from the heater element (3) to the substrate (1), the second heat conduction path being connected
15 at a second connection point (D) of the heater element and comprising the thin film material to be measured,

- a second measurement circuit part comprising a third electrically conductive path (BD) from a third contact (B) on the substrate to the second connection point (D) on the heater element and a fourth electrically conductive
20 path (DF) from the second connection point (D) to a fourth contact (F) on the substrate, the second measurement circuit part comprising the same materials as the first measurement circuit part, having a Seebeck coefficient in a predetermined range in the third (BD) and/or fourth electrically conductive path (DF).

11. A structure according to claim 10, wherein the second heat conduction path (DB) is formed on a short cantilever, and the fourth electrically conductive path (DF) is formed on a long cantilever, and the electrical resistance of the heater element is at least 20 times larger than the electrical resistance of the two short cantilevers combined together in series.

12. A structure according to any one of the previous claims, wherein the predetermined range of the Seebeck coefficient is a value higher than 50 $\mu\text{V/K}$ in absolute value.

13. A structure according to any one of the previous claims, wherein the first heat conduction path (CA) is made of the same material as the heater element (3), having an electrical resistivity between 1 $\text{m}\Omega\cdot\text{cm}$ and 1000 $\text{m}\Omega\cdot\text{cm}$;

14. A structure according to any one of the previous claims, wherein the first heat conduction path (CA) is made of the same material as the heater element (3), having an electrical resistivity between 10 mΩ.cm and 100 mΩ.cm;

5 15. A structure according to any one of the previous claims, wherein the first electrically conductive path (AC) and the second electrically conductive path (CE) are made of semi-conducting materials with opposite doping type.

16. A structure according to any one of the previous claims, wherein:

- the substrate (1) is a Si₃N₄-coated Si substrate;
- the first heat conduction path (CA) is made of p-type poly-SiGe;
- 10 - the heating element (3) is made of p-type poly-SiGe;
- the second electrically conductive path (CE) is made of n-type poly-SiGe;

17. A method for determining the thermal conductivity of a thin film material by means of a structure according to any one of the previous claims, comprising the steps of:

- 15 a) determining the Seebeck coefficients of the materials of the first and second electrically conductive paths (AC, CE) ;
- b) applying an AC voltage (V1) over the heater circuit part, while measuring the current (I) through the heater circuit part ;
- c) measuring the DC voltage difference (V2) between the first and second
- 20 contacts (A, E) on the substrate ;
- d) determining the thermal conductivity of the thin film material, using the Seebeck coefficients determined in step (a), using the injected power determined from the values (V1) and (I) of step (b), and using the measured DC voltage difference (V2) of step (c).

25 18. A method for determining the thermal conductivity of thin film insulator material, comprising the step of performing a differential measurement performed according to claim 17, on two test structures according to any one of the claims 1-16, one with and one without the thin film material to be measured deposited on top of at least the first heat conduction path (CA).

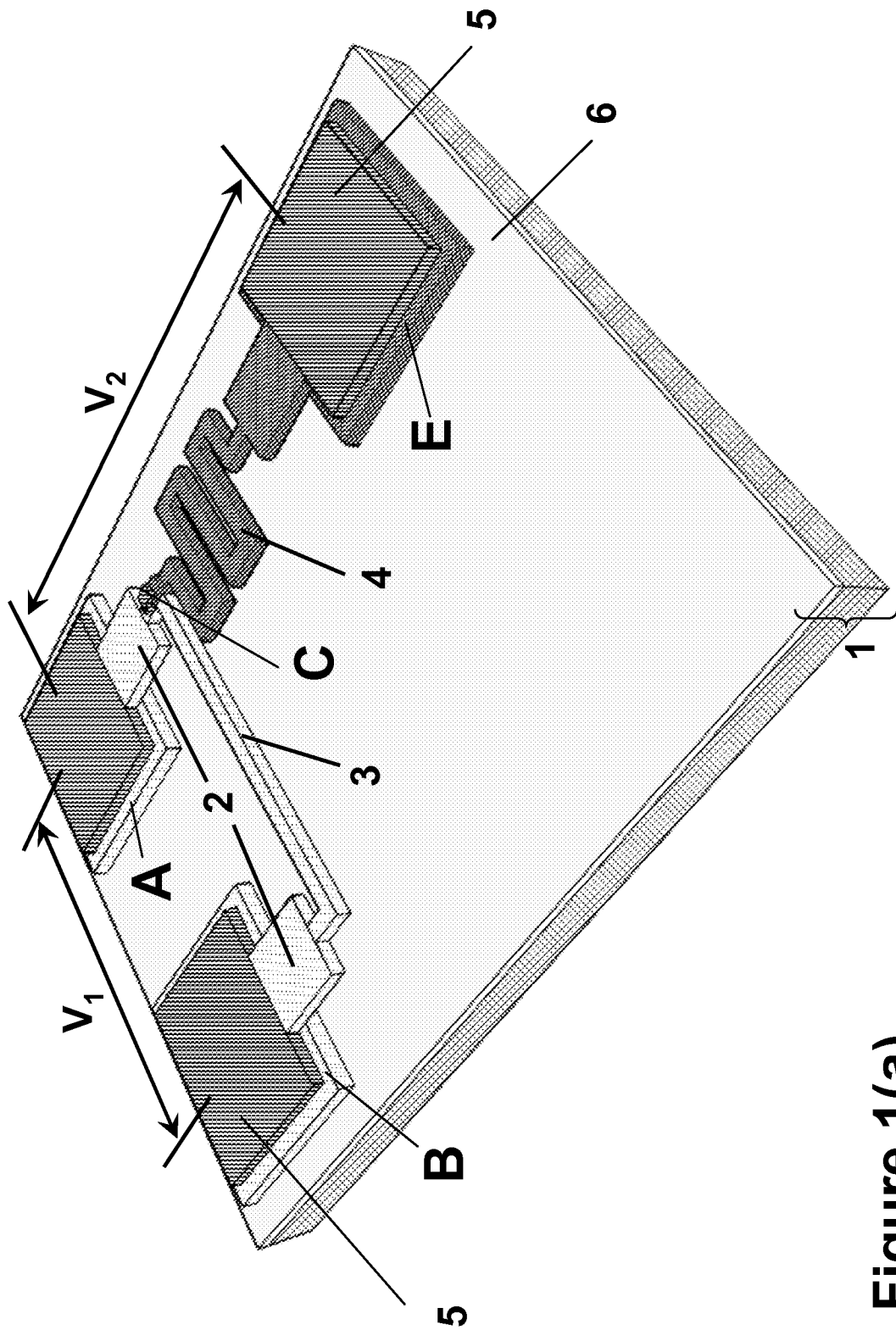


Figure 1(a)

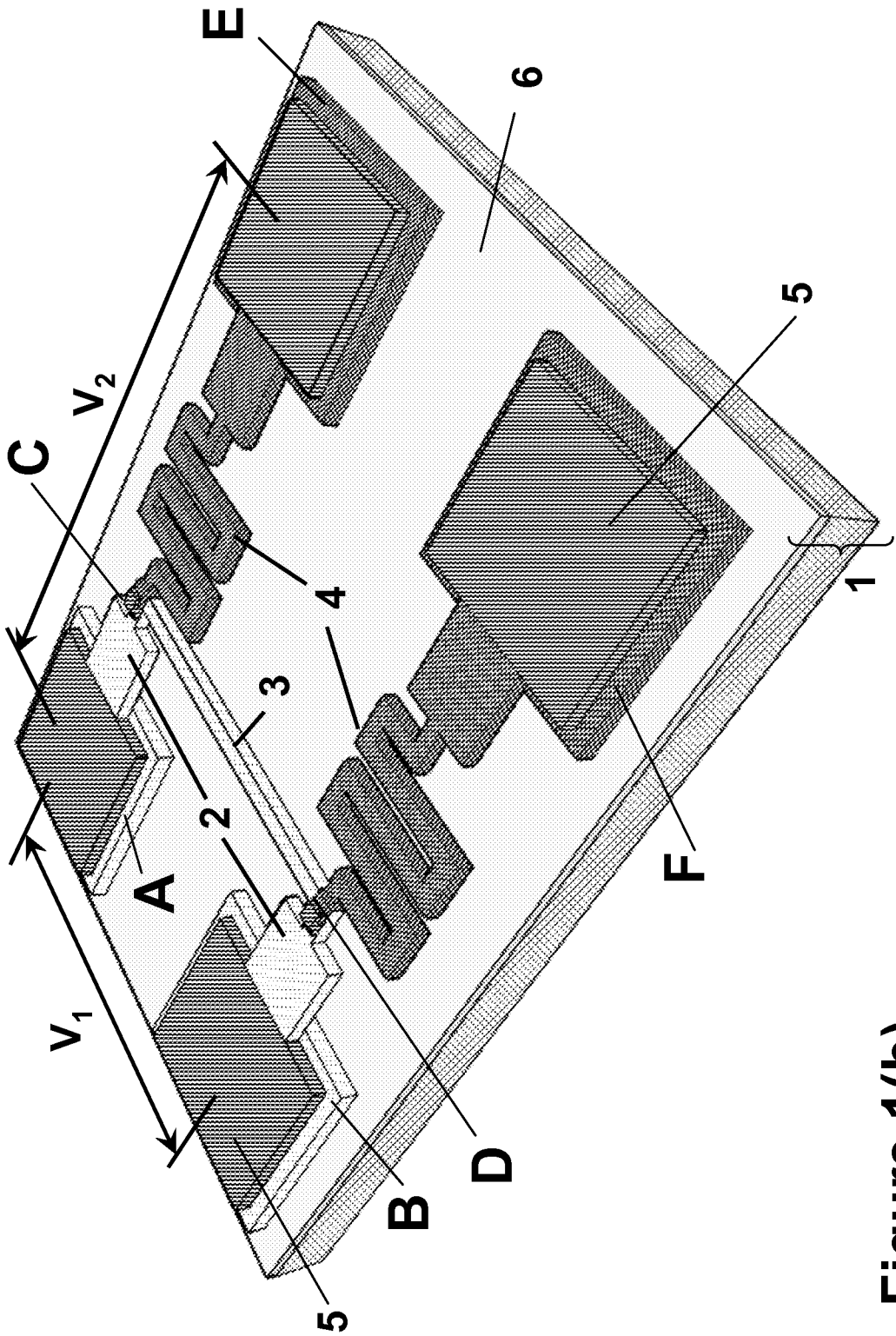


Figure 1(b)

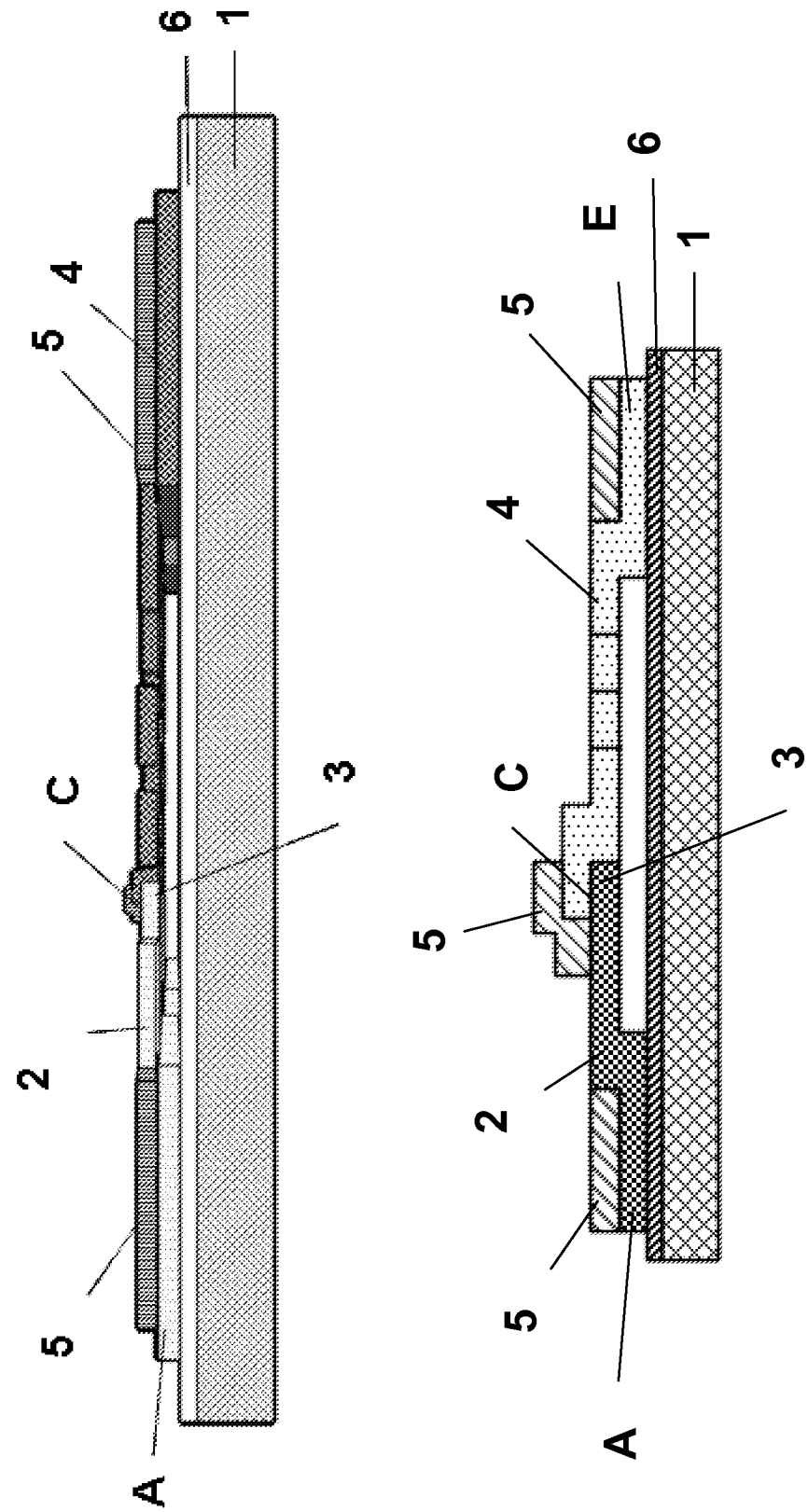


Figure 2(a)

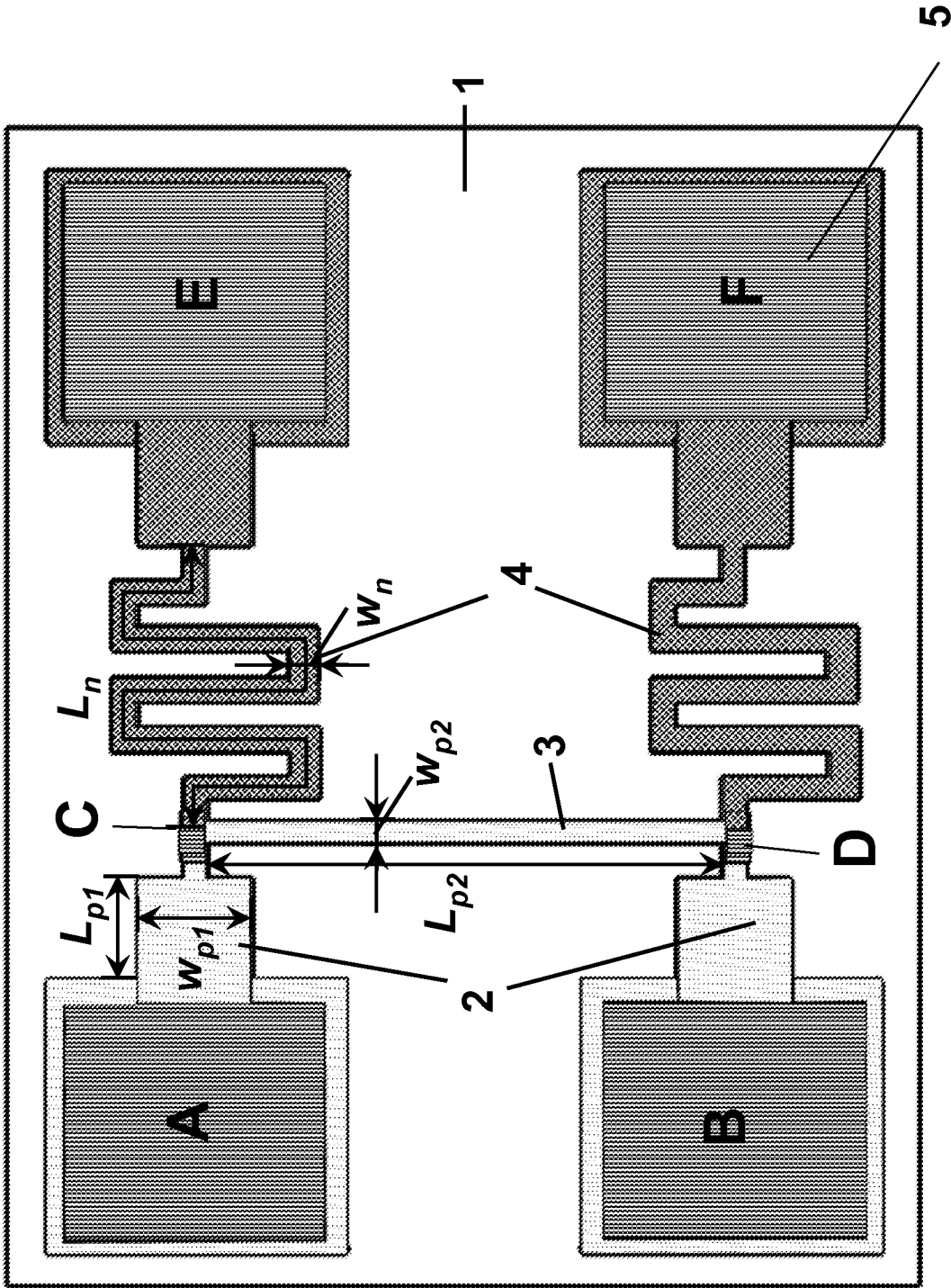


Figure 2(b)

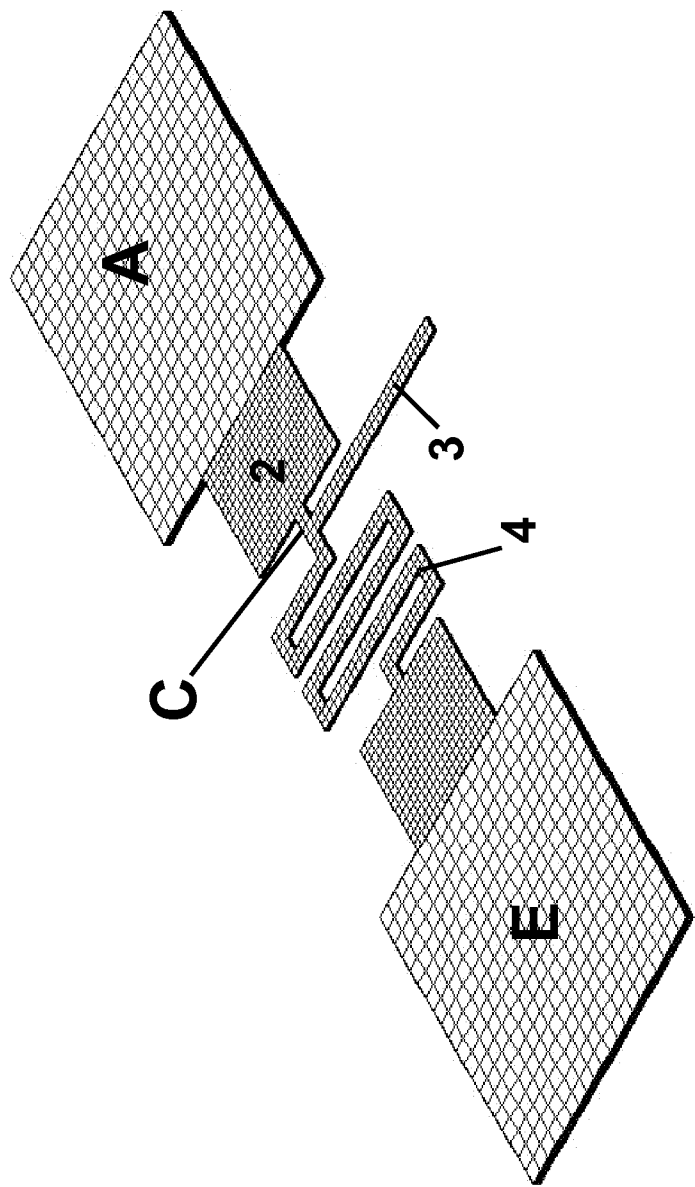
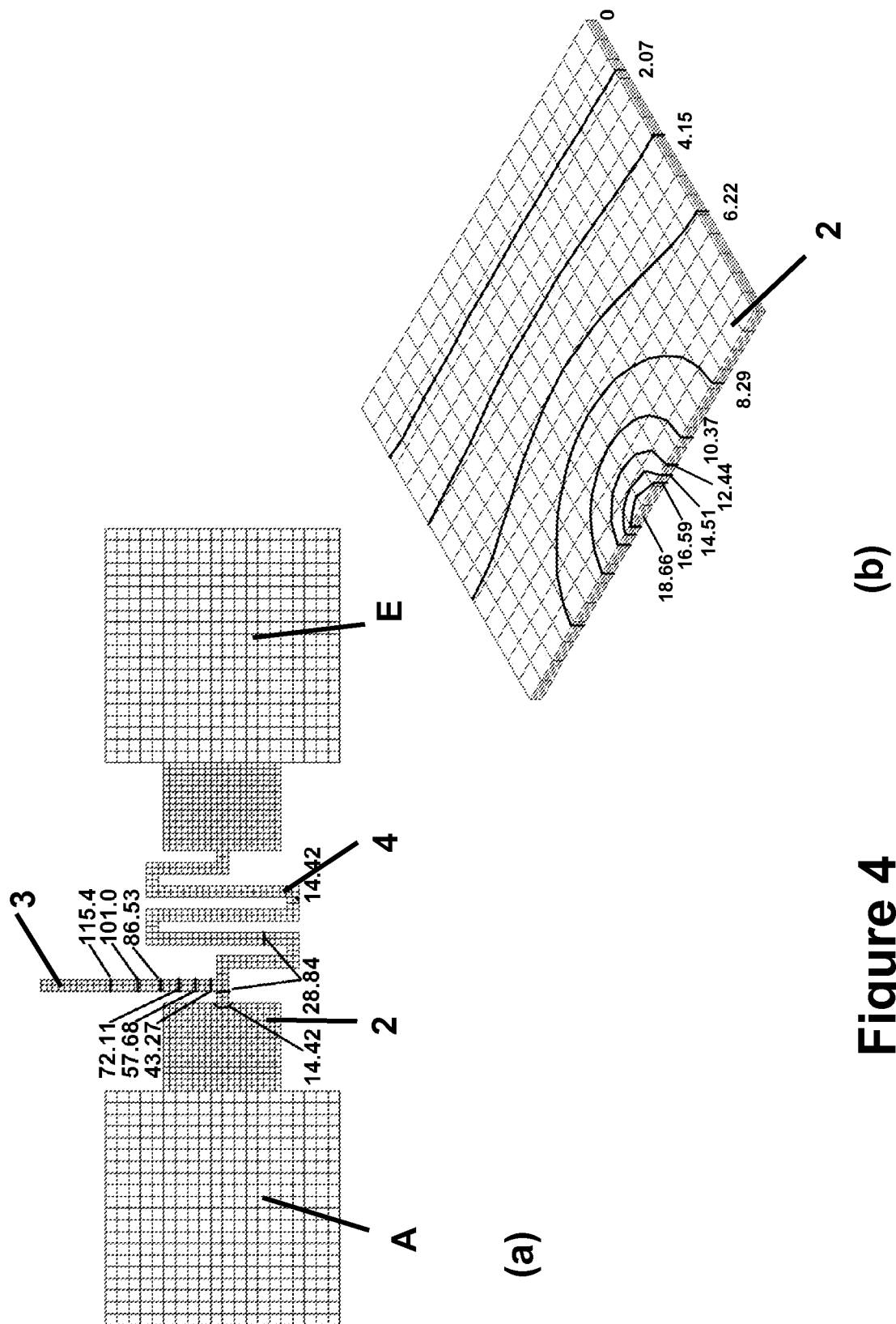


Figure 3



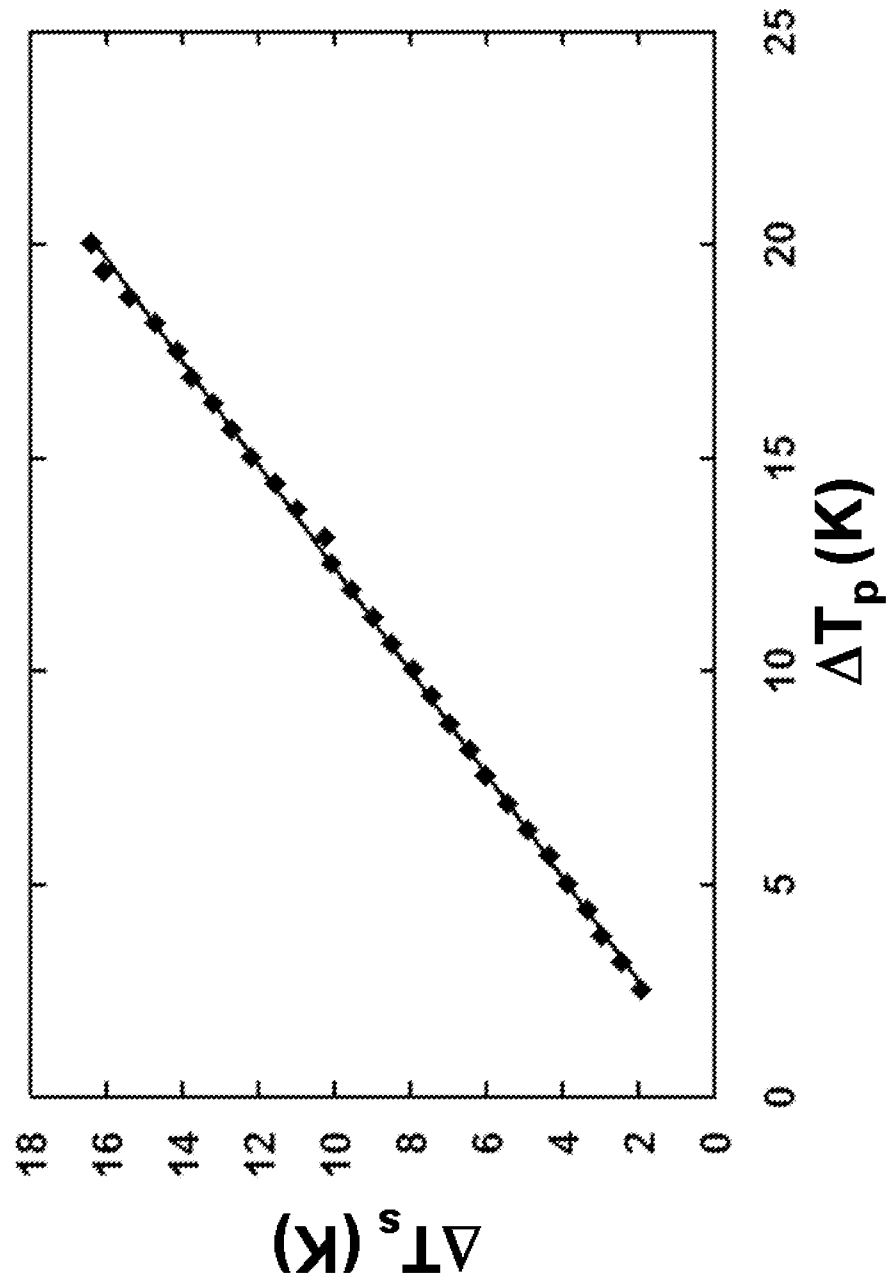


Figure 5

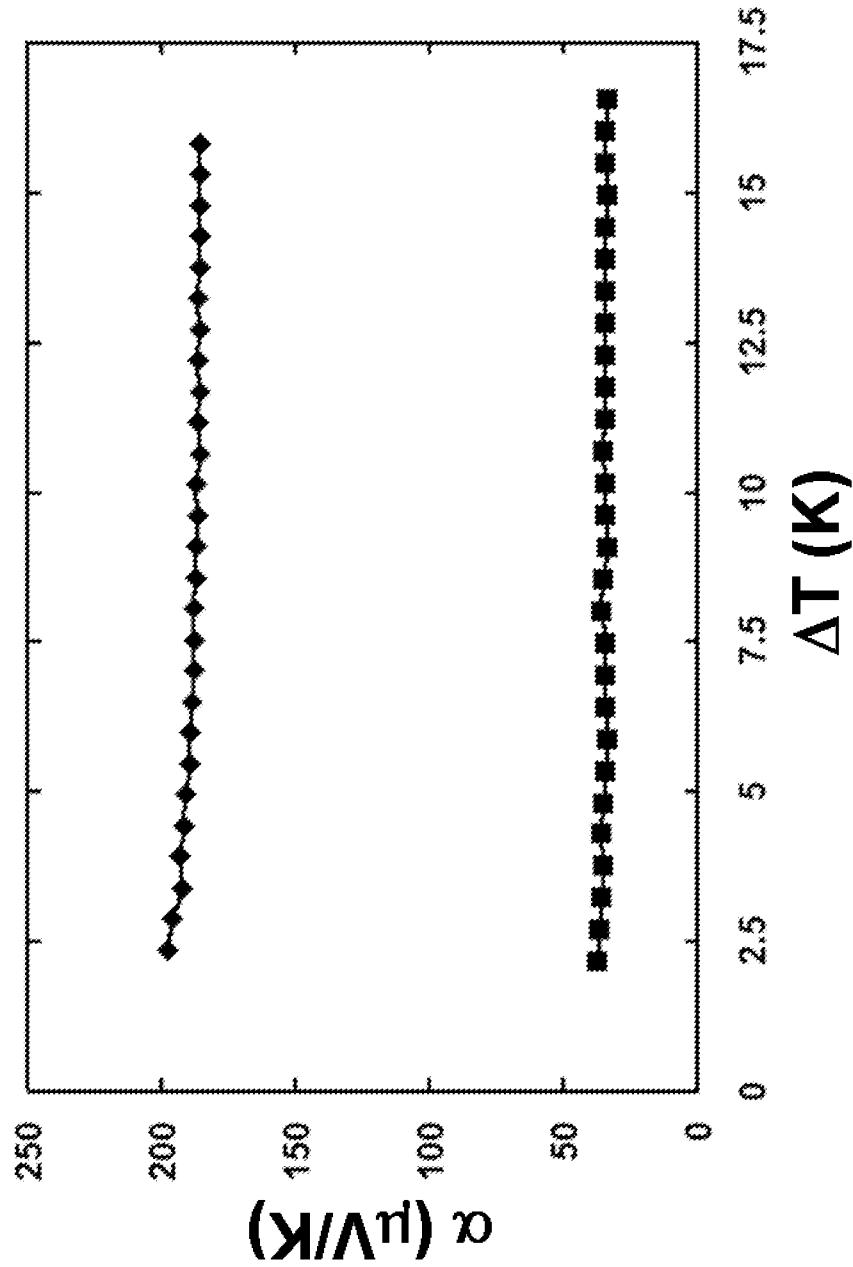


Figure 6

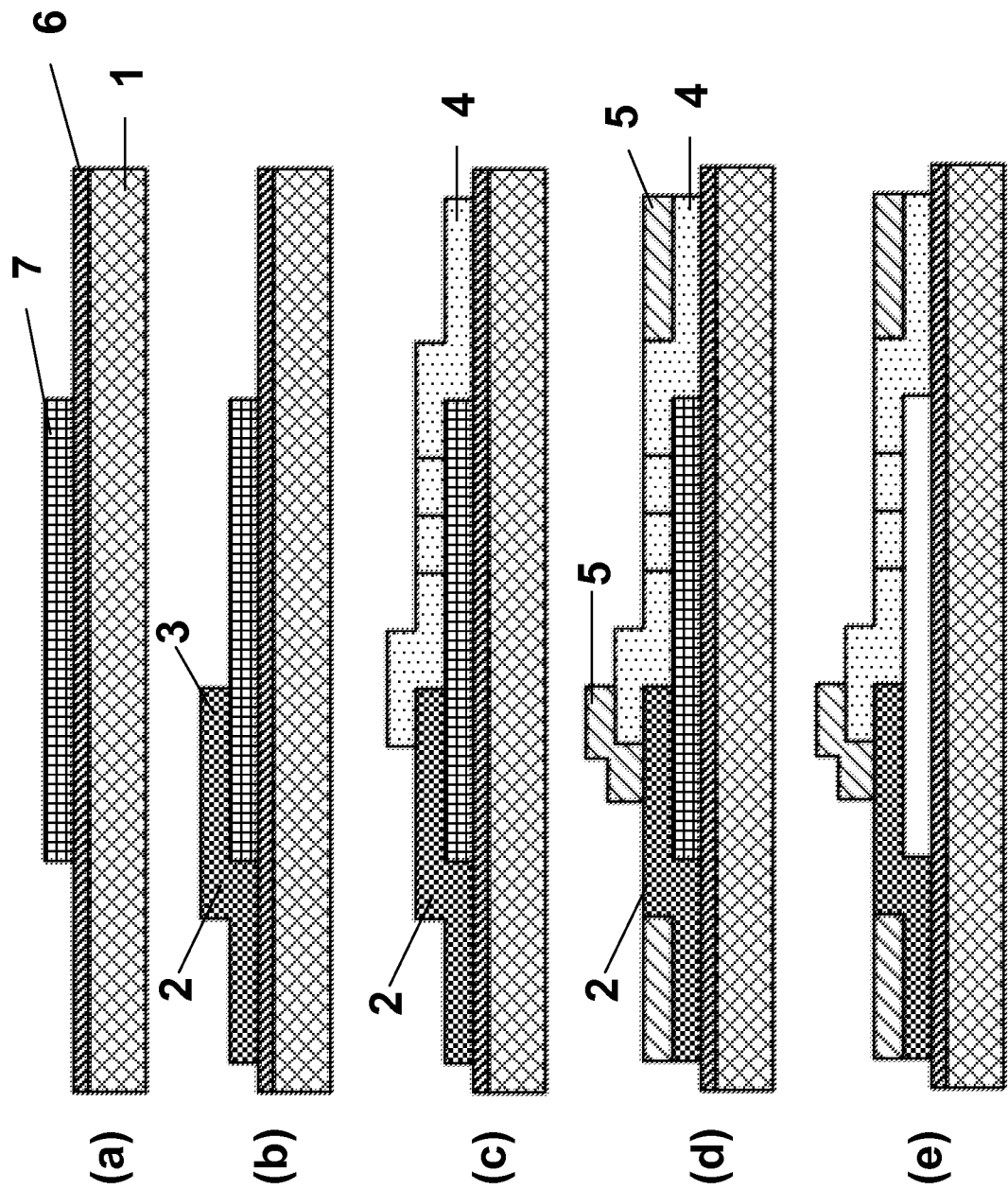
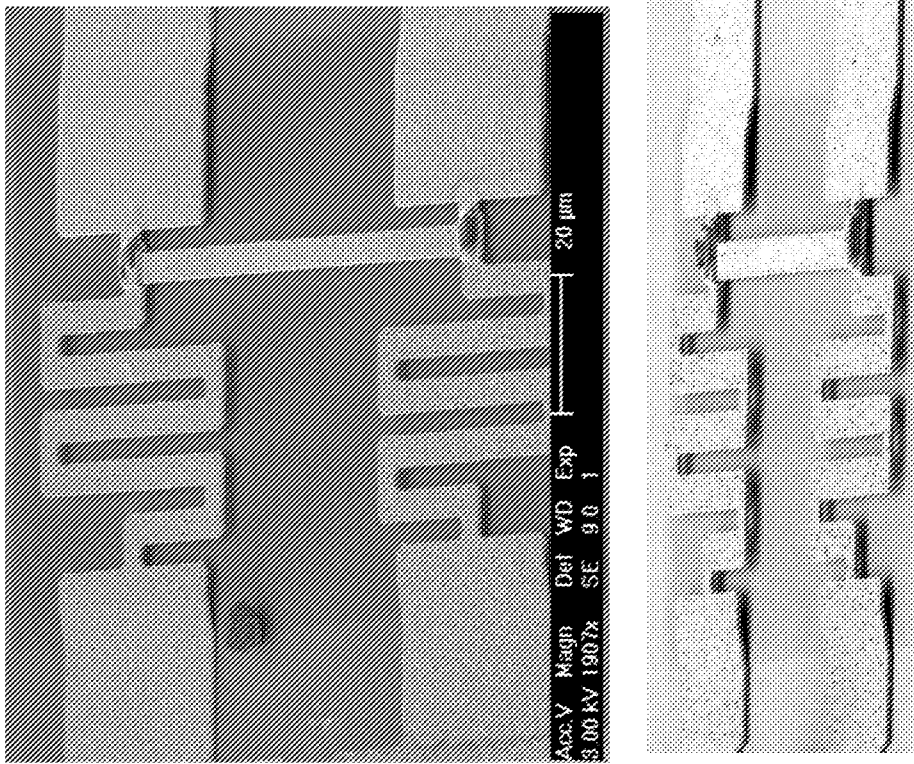


Figure 7

**Figure 8**

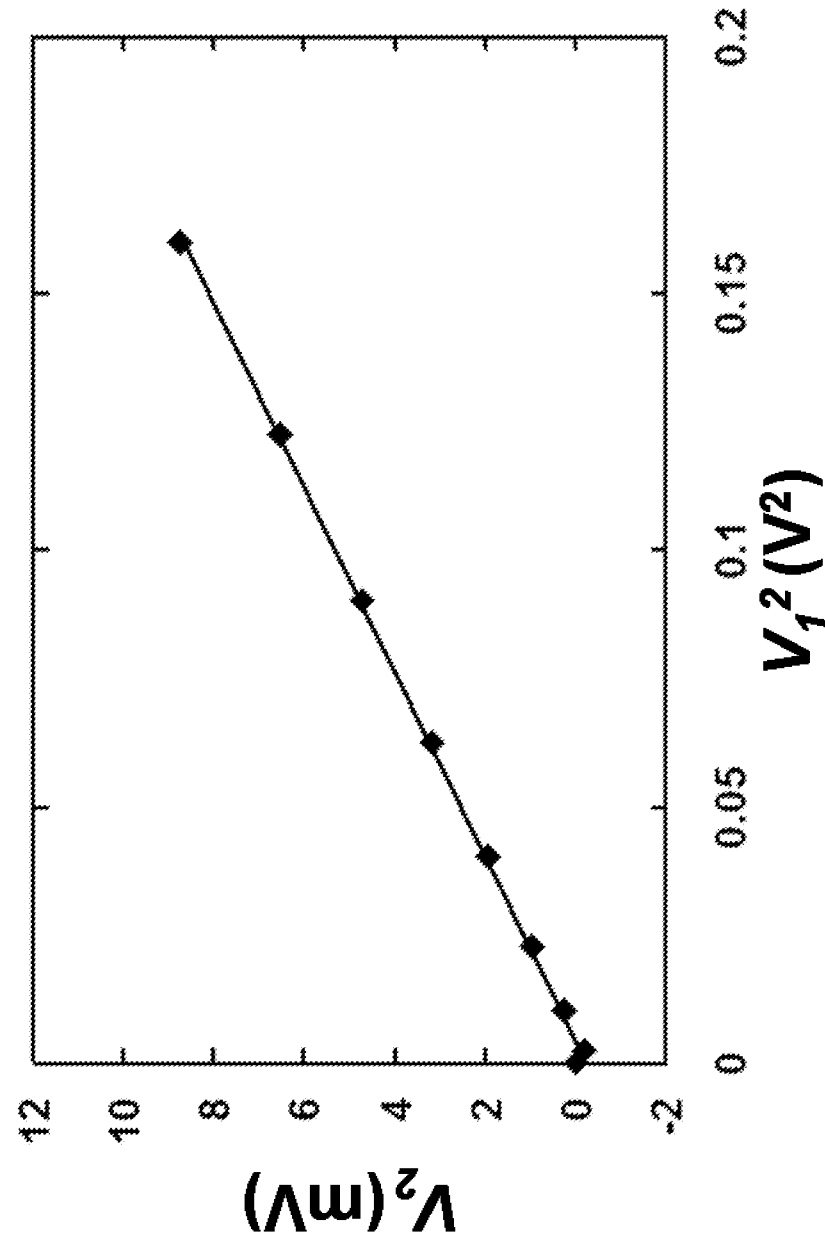


Figure 9

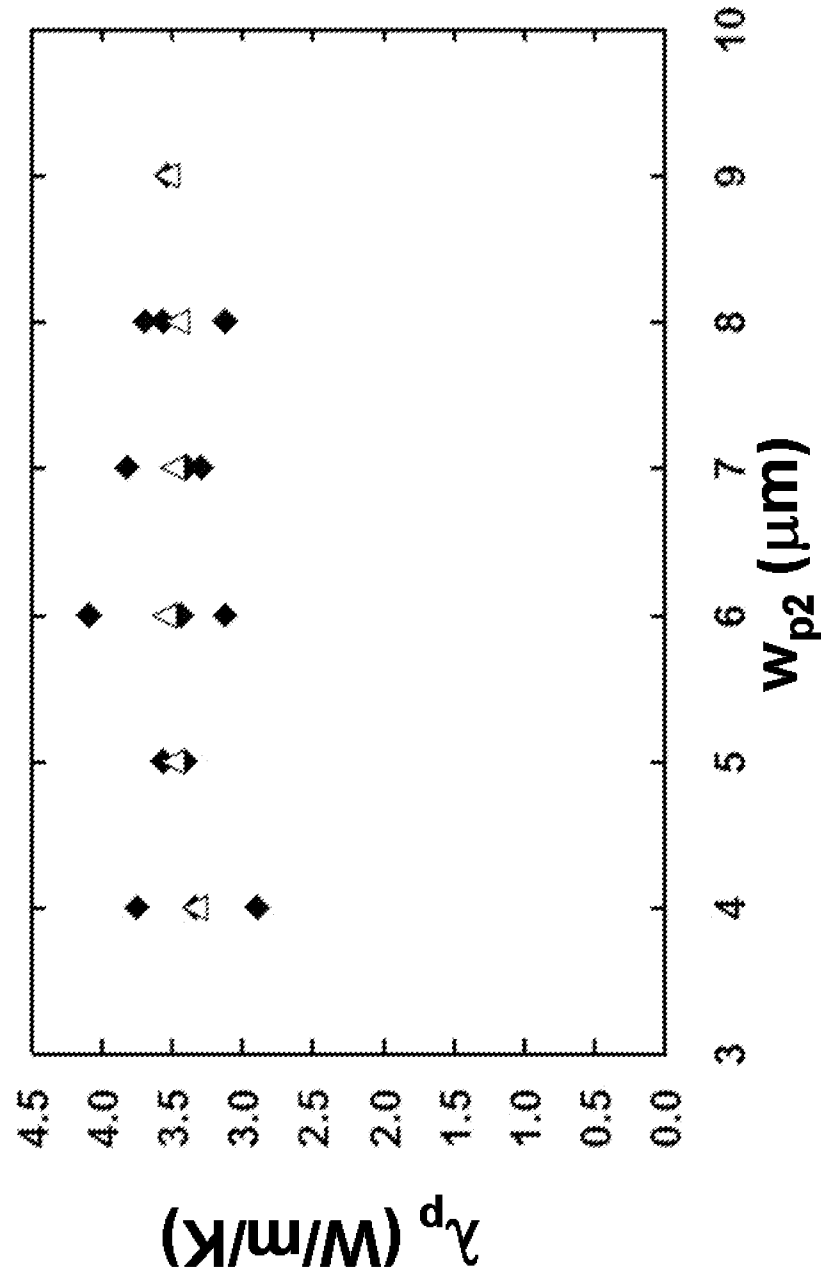


Figure 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2009/053367

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01N25/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N H01L G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 1 445 535 A (UNIV DONGNAN [CN]) 1 October 2003 (2003-10-01) cited in the application	1,3,5,7
Y	the whole document	17,18
A		2,4,6, 8-16
Y	LA SPINA L ET AL: "Bulk-Micromachined Test Structure for Fast and Reliable Determination of the Lateral Thermal Conductivity of Thin Films" JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 16, no. 3, 1 June 2007 (2007-06-01), pages 675-683, XP011187752 ISSN: 1057-7157	17,18
A	the whole document	1-16

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

8 document member of the same patent family

Date of the actual completion of the international search

27 July 2009

Date of mailing of the international search report

03/08/2009

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Authorized officer

Filipas, Alin

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2009/053367

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 44 10 315 A1 (INST PHYSIKALISCHE HOCHTECH EV [DE]) 30 November 1995 (1995-11-30) abstract; figure 1 -----	1,17
A	DE 10 2004 022206 A1 (BUNDESREP DEUTSCHLAND [DE]) 1 December 2005 (2005-12-01) abstract -----	1,17
A	JP 2007 024603 A (TOYOTA MOTOR CORP; UNIV TOHOKU) 1 February 2007 (2007-02-01) abstract -----	1,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2009/053367

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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DE 4410315	A1	30-11-1995	NONE	
DE 102004022206	A1	01-12-2005	NONE	
JP 2007024603	A	01-02-2007	NONE	