

METHOD AND DEVICE FOR SELECTIVELY MODIFYING
THE LAYER MORPHOLOGY IN SUPERCONDUCTORS

5 The invention relates to a method and a device for selectively modifying the layer morphology in superconductors by phase transformation and structuring through the application of a local heat input.

10 Superconductors, especially high-temperature superconductors (HTS) such as yttrium-barium-copper oxide (YBCO) and other cuprate-based or iron-based superconductors, are finding more and more applications, for example in quantum technology, cryoelectronics, power electronics and telecommunica-
15 tions. However, in order to utilize superconductors in these fields of application, microtechnical production of superconducting structures is necessary. Until now, such production has required complex processes. First, a layer of the superconducting material is deposited onto a carrier substrate using a common thin-film technology coating process, such as physical vapor deposition (PVD), molecular-beam epitaxy (MBE), pulsed laser deposition (PLD), electrochemical deposition (ECD), reactive evaporation (RE) or chemical vapor

deposition (CVD). This is followed by heat treatment at high temperatures to convert the material into a superconducting phase. Structuring may only take place afterwards. However, as HTSs in particular are compositions of several elements with highly anisotropic crystalline structures, etching processes to produce precisely defined structures are often difficult. Reactive ion etching (RIE) or ion beam etching (IBE) is typically used for structuring. However, these complex methods lead to rapid degradation of the layers and are therefore limited to a layer thickness of 50 nm to 100 nm. Alternatively, wet-chemical structuring methods and pulsed laser ablation (PLA) are also used to create structures, although both methods also have a number of disadvantages. For example, wet-chemical methods lead to a deterioration of the superconducting properties due to chemical degradation of the surfaces. With laser ablation, on the other hand, material damage may occur in the region of the structure edges, wherein the width of the damaged zone depends on the layer thickness, the laser radiation used and the number and duration of the laser pulses. As the laser pulses cause the material to heat up, laser ablation may also lead to a loss of oxygen in the material and therefore to a deterioration of the superconducting properties.

The object of the present patent application is therefore to solve the aforementioned problems and to propose a method and a device for the local phase transformation and structuring of thin films of superconducting materials, with which superconducting structures may be produced in a simple, reliable and easily scalable manner.

This object is achieved by a method according to independent claim 1 and by a device according to claim 18.

A method for the local phase transformation and structuring of thin films of superconducting materials comprises in particular the following steps:

depositing a thin film of a superconducting material in a ceramic or insulating phase on a carrier substrate in a deposition system,

inputting heat locally into the thin film, wherein regions of the thin film are heated and undergo a phase transformation into a superconducting phase, so that regions of the superconducting phase form structures embedded in the insulating phase.

The method may be used for a variety of common superconductor materials, such as high-temperature superconductors from the group of cuprate-based superconductors, such as YBCO, REBaCuO or BiSCCO, or iron-based superconductors, such as iron pnictides or iron selenides, to obtain high-temperature superconductor structures. However, it may also be used for other metal superconductors, A15 phases and amorphous or crystalline alloys in order to achieve changes in the layer morphology in these. In the following, the superconducting material is referred to as a thin film.

All common deposition and coating methods used in thin-film technology, such as physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), pulsed laser deposition (PLD), electrochemical deposition (ECD) or printing processes may be used to deposit the thin film of superconducting material. The deposition system is a device configured for the corresponding method. The thin film is deposited in an oxygen atmosphere. Different atmospheric conditions, such as gas composition, gas pressure and temperature, may favor defined layer growth. The carrier substrate may be constituted by semiconductor materials, ceramics, glass, metal, diamond or polymers. The substrate temperature also influences the layer production. As a rule, a substrate temperature of over 500°C is used for the deposition of HTS materials, while temperatures of around 400°C are used for iron-based superconductors. After deposition, the superconducting material is present in a ceramic or insulating phase on the carrier substrate.

The local heat input is used to selectively modify the layer morphology and thus simultaneously fulfills the tasks of the heat treatment and structuring process steps in the conventional production process chain for superconductor structures. The local heat input may take place simultaneously for several structures or groups of structures in one process step and thus offers particular advantages over writing methods such as laser ablation. The local heat input may take place after the deposition or during the deposition of the thin film. The local heat input may also take place in the deposition system, hereinafter referred to as in-situ, or outside the deposition system, hereinafter referred to as ex-situ. The local heat input heats regions of the thin film sufficiently so that a phase transformation from the ceramic/insulating phase to the superconducting phase takes place in these regions. As this transformation only takes place in certain regions, structures are simultaneously

formed in the superconducting phase, which are embedded in the surrounding initial phase. By controlling the local heat input, the desired geometries of the superconducting structures may be achieved. The result is a material composite of superconducting and non-superconducting regions without additional layer removal or application. An additional process step for structuring is therefore not required.

The local heat input may take place together with heating of the carrier substrate. An increased substrate temperature is usually necessary, especially when depositing the thin film. The local heat input may therefore also be used to heat the carrier substrate or supplement an existing substrate heating. In the latter case, the local heat input may be used to increase the thermal energy provided by the substrate heating locally and selectively so that the temperature required for a phase transformation is reached in certain regions of the thin film.

The local heat input may take place directly by means of induction heating of the thin film. At least one induction coil is used to induce eddy currents directly into regions of the thin film, which heat the material through its internal resistance. The geometry of the induction coil determines the geometry of the heated regions and thus also the resulting structures. The induction coil may, for example, be integrated into a substrate holder of the deposition system, the so-called chuck. Alternatively, the induction coil may also be arranged externally, for example above the surface of the thin film.

Induction heating may be provided by an induction coil that is integrated into the carrier substrate of the thin film. The induction coil is embedded in a layer of electrically insulating material, which is arranged on the carrier substrate. In this case, the carrier substrate may form a layer stack comprising layers of insulating material with an integrated induction coil, onto which the thin film is then deposited. Since the induction coil is provided on the carrier substrate, its properties may be predetermined individually for each desired structure.

Instead of heating the thin film directly by means of induction, the local heat input may also take place indirectly by means of heat conduction from a trigger material. The trigger material is arranged on the carrier substrate of the thin film. In this case, the carrier substrate may form a layer stack comprising

layers of insulating material with trigger material embedded therein and a possibly integrated induction coil, onto which the thin film is then deposited. The trigger material may be arranged in any geometries. Induction coils, for example in the substrate holder or also in the carrier substrate, in turn induce eddy currents in the trigger material, causing it to heat up. Due to the thermal conductivity of the trigger material, the thin film is also heated in certain regions. In addition to electrical conductivity, the trigger material should therefore also have good thermal conductivity. Materials such as copper, silver or, in particular, titanium, which also has a high melting temperature, are therefore particularly suitable. The geometry of the trigger material on the carrier substrate thus also determines the geometry of the superconducting structures to be generated. The use of a trigger material results in greater flexibility in the manufacture of the structures, as the geometry of the induction coil does not necessarily have to be changed when the desired structure geometry is changed.

Alternatively, the local heat input may also take place indirectly by means of resistance heating using resistive heating elements. The resistive heating elements may be integrated on the carrier substrate of the thin film and electrically contacted in order to heat the thin film in certain regions by thermal conduction. The resistive heating elements may be arranged in an electrically insulating layer on the carrier substrate. The geometry of the resistive heating elements may be used to specify the geometry of the structures to be produced.

Local heat input by means of one of the methods described above may take place in-situ in the deposition system under an oxygen atmosphere. In this way, no additional heating device, as used in conventional heat treatments, is required and the process costs may be reduced. The deposition system may be adapted accordingly to enable local heat input, for example with induction coils or additional contacts for connecting resistive heating elements. Preferably, the local heat input may take place in-situ already during the deposition of the thin film. The resulting thin film is heated locally more than the substrate already during the deposition process, so that the superconducting material undergoes a phase transformation into the superconducting phase in some regions. In this way, the process time for manufacturing superconducting structures may be further reduced.

Alternatively, the local heat input may also take place ex-situ in an additional heating chamber under an oxygen atmosphere. Although the use of an additional heating chamber for local heat input separates the process steps of deposition and local heat input, there are more possibilities for local heat input, for example by heating the surface of the thin film.

The local heat input may also take place during deposition in the deposition system and may be completed by further heat treatment ex-situ in a heating chamber. For this purpose, the thin film is heated locally during deposition in order to stimulate the localized phase transformation into the superconducting phase. Subsequent heat treatment in the heating chamber then selectively converts these regions completely into the superconducting phase, while the surrounding regions remain in the ceramic phase.

In particular, the thin film may be a high-temperature superconductor film. Since the known HTS materials, such as YBCO, REBaCuO, BiSCCO or iron-based high-temperature superconductors, are difficult to structure using conventional methods or experience reductions in their performance due to conventional structuring processes, the method according to the invention is particularly suitable for these materials in order to produce superconducting structures or geometries.

The thin film may also consist of other metal superconductors, A15 phases and amorphous or crystalline alloys. With these materials too, it may be advantageous to combine heat treatment and structuring. At the same time, further improved properties, such as increased ductility, may also be achieved by the method according to the invention.

Common methods such as PVD, CVD, ALD, PLD or ECD may be used to deposit the thin film. The thin film may also be produced using a printing process. The method is therefore extremely flexible with regard to the deposition method of the thin film, and therefore also with regard to the superconducting material to be processed. Furthermore, these conventional methods may be utilized for the method according to the invention without any great additional process effort.

In this context, a layer with a thickness of less than 100 μm may be regarded as a thin film. Layers of this size are relevant for microtechnical applications.

At the same time, the method according to the invention reliably enables the modification of the layer morphology of such layers.

5 The method described also offers great flexibility with regard to the carrier substrates used. For example, the carrier substrate may be pre-structured three-dimensionally in order to achieve additional effects or to enable subsequent application. While such pre-structuring of the substrate would make structuring of the superconducting material by many conventional methods more difficult, it has no negative influence on the selective modification by the method according to the invention. This method may also be used to process carrier substrates and thus thin films of superconducting materials to chip, wafer or even panel size, as the methods for local heat input may also be easily scaled to larger areas.

10 Due to the local heat input, temperatures between 200°C and 2000°C may be reached in the thin film. In this way, phase transformations into the superconducting phase may be achieved in thin films of relevant superconducting materials. The method according to the invention thus enables the production of superconducting structures from a large number of superconductors.

15 A device for local phase transformation and structuring of thin films of superconducting materials, comprises

20 a deposition system for depositing a thin film of a superconducting material in a ceramic or insulating phase on a carrier substrate, and

25 a device for inputting heat locally into the thin film, wherein regions of the thin film are heated and undergo a phase transformation into a superconducting phase, so that regions of the superconducting phase form structures embedded in the insulating phase.

30 The deposition system may utilize coating methods commonly used in thin-film technology to deposit a thin film of superconducting material in a ceramic or insulating phase. Different atmospheric conditions, such as gas composition, gas pressure and temperature, may favor defined layer growth here. After deposition, the superconducting material is present in a ceramic or insulating phase on the carrier substrate.

The layer morphology is selectively modified by the device for local heat input. It therefore simultaneously carries out the heat treatment and structuring process steps of the conventional production process chain for superconductor structures. The device for local heat input may be part of the deposition system, so that the local heat input takes place in-situ, or may be provided externally as an independent device, so that the local heat input takes place ex-situ.

The device for local heat input may be configured to also heat the carrier substrate, for example to favor the deposition process of the thin film.

The device for local heat input may comprise at least one induction coil. This may be arranged in a substrate holder. At least one induction coil induces eddy currents directly into regions of the thin film, which heat the material through its internal resistance. The geometry of the induction coil determines the geometry of the heated regions and thus also the resulting structures. Alternatively, the induction coil may also be arranged externally, for example above the surface of the thin film.

The induction coil may be integrated into the carrier substrate of the thin film. The induction coil may be embedded in a layer of electrically insulating material, which is arranged on the carrier substrate. Since the induction coil is provided on the carrier substrate, its properties may be predetermined individually for each desired structure.

The carrier substrate may comprise a trigger material that is heated by induction heating. The trigger material may be embedded in an electrically insulating layer. The trigger material may be arranged in any geometries. The induction coil in turn induces eddy currents in the trigger material, causing it to heat up. Due to the thermal conductivity of the trigger material, the thin film is also heated in certain regions. In addition to electrical conductivity, the trigger material should therefore also have good thermal conductivity and a high melting temperature. Materials such as copper, silver or titanium are therefore particularly suitable. The geometry of the trigger material on the carrier substrate thus also determines the geometry of the superconducting structures to be generated. The use of a trigger material results in greater flexibility in the manufacture of the structures, as the geometry of the induction coil

does not necessarily have to be adapted when the desired structure geometry is changed

5 Alternatively, the device for local heat input may comprise resistive heating elements. The resistive heating elements may be integrated on the carrier substrate of the thin film and electrically contacted in order to heat the thin film in certain regions by thermal conduction. The resistive heating elements may be arranged in an electrically insulating layer on the carrier substrate. The geometry of the resistive heating elements may be used to specify the geometry of the structures to be produced.

10 The device for local heat input may be formed as part of the deposition system. The deposition system may be adapted accordingly to enable local heat input, for example with induction coils or additional contacts for connecting resistive heating elements. Preferably, the device for local heat input may be configured to carry out the local heat input already during the deposition of the thin film. The resulting thin film is heated locally more than the substrate already during the deposition process, so that the superconducting material undergoes a phase transformation into the superconducting phase in some regions. In this way, the process time for manufacturing superconducting structures may be further reduced.

20 Alternatively, the device for local heat input may also be provided as an external heating chamber. The heating chamber may be a heating chamber as used for conventional heat treatments, which is adapted for the methods described above for local heat input and is equipped, for example, with induction coils or additional contacts for connecting resistive heating elements. However, the heating chamber may also be an arrangement customized to the specific methods for local heat input.

The device for local heat input may also be configured to carry out the local heat input in-situ already during the deposition in the deposition system and subsequently carry out a further heat treatment ex-situ.

30 The deposition system may be configured to deposit a high-temperature superconductor film. Since the known HTS materials, such as YBCO, REBaCuO, BiSCCO or iron-based high-temperature superconductors, are difficult to

structure using conventional methods or experience reductions in their performance due to conventional structuring processes, the device according to the invention is particularly suitable for these materials in order to produce superconducting structures.

5 However, the deposition system may also be configured to deposit other metal superconductors, A15 phases and amorphous or crystalline alloys. The device according to the invention also simplifies the production of superconducting structures for these methods.

10 The deposition system may use a common process such as PVD, CVD, ALD, PLD or ECD to deposit the thin film. The deposition system may also be configured to produce the thin film using a printing process.

In this context, a layer with a thickness of less than 100 μm may be regarded as a thin film. The device described enables selective modification of the layer morphology of such layers.

15 The deposition system may be configured to deposit thin films onto three-dimensionally pre-structured carrier substrates. The device according to the invention thus facilitates the production of three-dimensional structures from superconducting materials. The deposition system and the device for local heat input may also be configured to provide carrier substrates in chip, wafer
20 and panel size with superconducting structures. The described device for local phase transformation and structuring of thin films of superconducting materials may therefore be used to produce large-area superconducting structures.

25 The local heat input device may be configured to reach temperatures between 200°C and 2000°C in the thin film and may therefore initiate a phase transition to the superconducting phase in a variety of relevant superconducting materials.

30 The method according to the invention, as well as the device according to the invention, may thus solve a large number of problems that arise in the micro-technical production of superconducting structures. A material composite of superconducting phase and insulating phase may be produced from a thin film in a simple way so that the superconducting structures are electrically insulated from each other. As there is no subsequent structuring by means of

etching processes or laser ablation, the structures do not suffer any damage that could reduce their performance. Production may be carried out in-situ to further reduce process times and equipment costs.

5 The described embodiments of the method and the device for local phase transformation and structuring of thin films of superconducting materials may be used individually or combined to achieve additional effects and to simplify the production of structures of superconducting materials and to enable them for a variety of materials and regions of application.

10 The above-mentioned and other aspects of the invention will become apparent from the detailed description of the exemplary embodiments, which is given with the aid of the following figures:

Fig. 1 schematically illustrates an embodiment of the method according to the invention,

15 Fig. 2 schematically illustrates a further embodiment of the method according to the invention,

Fig. 3 schematically illustrates a further embodiment of the method according to the invention,

Fig. 4 schematically illustrates a further embodiment of the method according to the invention,

20 Fig. 5 schematically illustrates a further embodiment of the method according to the invention,

Fig. 6 schematically illustrates a further embodiment of the method according to the invention,

25 Fig. 7 schematically illustrates a further embodiment of the method according to the invention,

Fig. 8 schematically illustrates a further embodiment of the method according to the invention,

Fig. 9 schematically illustrates a further embodiment of the method according to the invention, and

Fig. 10 schematically illustrates a further embodiment of the method according to the invention.

In the following, the claimed method will be explained in greater detail on the basis of the accompanying drawings. Like reference signs refer to like elements.

Fig. 1 to 5 schematically illustrate methods according to the invention and the devices used, in which the local heat input takes place in-situ with the deposition system 3. Fig. 6 to 10, on the other hand, show methods according to the invention and the devices used, in which the local heat input takes place ex-situ with a heating chamber 12.

The figures show the step of local heat input into the thin film 1 and the resulting structures in the superconducting phase 8. The thin film 1 in the ceramic or insulating phase of the superconducting material is deposited beforehand on the carrier substrate 2 by a deposition system 3 in a process step not shown. Deposition may be carried out using a standard thin-film technology coating process such as PVD, CVD, ALD, PLD or ECD. The thin film 1 may also be produced using a printing process.

The carrier substrate 2 is a chip, a wafer or a panel made of semiconductor material, ceramic, glass, metal, diamond or polymer. The material of the carrier substrate is selected according to the intended use and the superconducting material used. The carrier substrate 2 may be heated by the device for local heat input during the deposition process.

The thin film 1 consists of a superconducting material. It may be a high-temperature superconductor from the group of cuprate-based superconductors, such as YBCO, REBaCuO or BiSCCO, or iron-based superconductors, such as iron pnictides or iron selenides. It may also be a superconducting material from the group of amorphous or crystalline alloys, metal superconductors or A15 phases.

Fig. 1 schematically illustrates the local heat input by means of direct induction heating into the thin film 1 in-situ in the deposition system 3. The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 arranged in the substrate holder 5.

The induction coil 6 generates an electromagnetic field 7 that induces eddy currents directly in the thin film 1. The thin film 1 is heated locally by the resistance of the film material. The arrangement of the induction coil 6 determines the geometry of the heated regions. Sufficient heating, between 200°C and 2000°C depending on the superconducting material used, causes a phase transformation from the ceramic or insulating phase of the superconducting material to the superconducting phase 8 in the regions affected by the local heat input. This results in structures of the superconducting phase 8 in the thin film 1, which are embedded in the non-converted phase and are thus insulated from each other.

Fig. 2 schematically illustrates a further embodiment of local heat input by means of direct induction heating into the thin film 1 in-situ in the deposition system 3. The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 arranged in the layer stack of the carrier substrate 2. This is embedded in an insulating layer 9. The induction coil 6 generates an electromagnetic field 7 that induces eddy currents directly in the thin film 1. The thin film 1 is heated locally by the resistance of the film material. The arrangement of the induction coil 6 determines the geometry of the heated regions. Since the induction coil 6 is integrated into the carrier substrate 2 in this embodiment, the entire substrate holder 5 does not have to be adapted to change the desired geometry of the structures to be generated. Instead, a separate carrier substrate 2 may be produced for each desired geometry.

Fig. 3 schematically illustrates the indirect local heat input by means of induction heating into a trigger material 10 and heat conduction into the thin film 1. The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 integrated into the substrate holder 5. The induction coil 6 generates an electromagnetic field 7 that induces eddy currents in the trigger material 10. This is embedded in an electrically insulating layer 9 of the carrier substrate 2. The resistance of the trigger material 10 heats it up. The local heating of the thin film 1 is caused by the thermal conduction of the trigger material 10 into the thin film 1. The arrangement of the trigger material on the carrier substrate determines the geometry of the heated regions. In this embodiment, the induction coil 6 is per-

manently integrated in the substrate holder 5, but the geometry of the superconducting phase 8 is determined by the geometry of the trigger material 10 on the carrier substrate 2, so that only the carrier substrate 2 needs to be modified if the desired geometry is changed.

5 The embodiment shown in Fig. 4 is similar to the embodiment shown in Fig. 3, but here both the induction coil 6 and the trigger material 10 are integrated into the layer stack of the carrier substrate 2. These are embedded in insulating layers 9, which could be two separate layers or one continuous layer. In this embodiment, the structures in the superconducting phase 8 are completely independent of the substrate holder 5.

Fig. 5 schematically illustrates the indirect local heat input by means of resistance heating of resistive heating elements 11. The local heat input takes place under oxygen atmosphere 4. The heating takes place by means of resistive heating elements 11 integrated into the layer stack of the carrier substrate 2. These are embedded in an electrically insulating layer 9. The resistance of the resistive heating elements causes them to heat up under current flow. The local heating of the thin film 1 is caused by the thermal conduction of the heating elements 11. The arrangement of the resistive heating elements 11 determines the geometry of the heated regions and thus also the geometry of the structures generated in the superconducting phase 8.

The embodiments shown in Fig. 1 to Fig. 5 have in common that the local heat input takes place in-situ in the deposition system 3. This allows the local heat input to take place simultaneously with the deposition of the thin film 1.

25 In Fig. 6, by contrast, the local heat input by means of direct induction heating into the thin film 1 ex-situ in the heating chamber 12 is shown schematically. The process otherwise corresponds to the embodiment shown in Fig. 1: The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 arranged in the substrate holder 5. The induction coil 6 generates an electromagnetic field 7 that induces eddy currents directly in the thin film 1. The thin film 1 is heated locally by the resistance of the film material. The arrangement of the induction coil 6 determines the geometry of the heated regions. Sufficient heating, between 200°C and 2000°C depending on the superconducting material used, causes a

phase transformation from the ceramic or insulating phase of the superconducting material to the superconducting phase 8 in the regions affected by the local heat input. This results in structures of the superconducting phase 8 in the thin film 1, which are embedded in the non-converted phase and are thus isolated from each other.

Fig. 7 schematically illustrates a further embodiment of local heat input by means of direct induction heating into the thin film 1 ex-situ in the heating chamber 12. The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 arranged in the layer stack of the carrier substrate 2. This is embedded in an insulating layer 9. The induction coil 6 generates an electromagnetic field 7 that induces eddy currents directly in the thin film 1. The thin film 1 is heated locally by the resistance of the film material. The arrangement of the induction coil 6 determines the geometry of the heated regions. Since the induction coil 6 is integrated into the carrier substrate 2 in this embodiment, the entire substrate holder 5 does not have to be adapted to change the desired geometry of the structures to be generated. Instead, a separate carrier substrate 2 may be produced for each desired geometry.

Fig. 8 schematically illustrates the indirect local heat input by means of induction heating into a trigger material 10 and heat conduction into the thin film 1 ex-situ in the heating chamber 12. The local heat input takes place under oxygen atmosphere 4. The induction heating takes place by means of an induction coil 6 integrated into the substrate holder 5. The induction coil 6 generates an electromagnetic field 7 that induces eddy currents in the trigger material 10. This is embedded in an electrically insulating layer 9 of the carrier substrate 2. The resistance of the trigger material 10 causes it to heat up. The local heating of the thin film 1 is caused by the thermal conduction of the trigger material 10. The arrangement of the trigger material on the carrier substrate determines the geometry of the heated regions. In this embodiment, the induction coil 6 is permanently integrated in the substrate holder 5, but the geometry of the superconducting phase 8 is determined by the geometry of the trigger material 10 on the carrier substrate 2, so that only the carrier substrate 2 needs to be modified if the desired geometry is changed.

The embodiment in Fig. 9 again corresponds to the embodiment shown in Fig. 8, but here again both the induction coil 6 and the trigger material 10 are integrated into the layer stack of the carrier substrate 2. These are embedded in insulating layers 9, which could be two separate layers or one continuous layer. In this embodiment, the structures in the superconducting phase 8 are completely independent of the substrate holder 5.

Fig. 10 schematically illustrates the indirect local heat input by means of resistance heating of resistive heating elements 11 ex-situ in the heating chamber 12. The local heat input takes place under oxygen atmosphere 4. The heating takes place by means of resistive heating elements 11 integrated into the layer stack of the carrier substrate 2. These are embedded in an electrically insulating layer 9. The resistance of the resistive heating elements causes them to heat up under current. The local heating of the thin film 1 is caused by the thermal conduction of the heating elements 11. The arrangement of the resistive heating elements 11 determines the geometry of the heated regions and thus also the geometry of the structures generated in the superconducting phase 8.

Although the use of an external heating chamber 12 requires an additional process step and the transfer of the carrier substrate 2 from the deposition system 3 to the heating chamber 12, it may also provide additional options for local heat input. For example, the induction coil 6, the trigger material 10 or the resistive heating elements 12 could also be arranged on the surface side, i.e., above the thin film 1 in the illustration of the figures, or even on both sides.

As is visible from the embodiments shown, the method according to the invention and the device according to the invention for the local phase transformation and structuring of thin films of superconducting materials enable the production of superconducting structures from a large number of superconducting materials. Compared to conventional methods, production requires fewer process steps and reliably delivers superconducting structures with favorable properties. Due to the good scalability of the local heat input methods used, the method may also be used for structuring larger areas, which enables industrial applicability.

5 The exemplary embodiments shown here are not limiting. In particular, the features of these exemplary embodiments may be combined with each other to achieve additional effects. It is obvious to a person skilled in the art that modifications may be made to these exemplary embodiments without departing from the fundamental principles of the subject matter of this patent application, the scope of which is defined in the claims.

Claims

- 5 1. A method for the local phase transformation and structuring of thin films of superconducting materials, said method comprising the steps of:
- 10 depositing a thin film (1) of a superconducting material in a ceramic or insulating phase on a carrier substrate (2) in a deposition system (3),
- inputting heat locally into the thin film (1), wherein regions of the thin film (1) are heated and undergo a phase transformation into a superconducting phase (8), so that regions of the superconducting phase (8) form structures embedded in the insulating phase.
- 15 2. The method according to claim 1, characterized in that the local heat input takes place together with heating of the carrier substrate (2).
3. The method according to claim 1 or 2, characterized in that the local heat input takes place by induction heating directly into the thin film (1) by means of an induction coil (6) arranged in a substrate holder.
- 20 4. The method according to claim 1 or 2, characterized in that the local heat input takes place by induction heating directly into the thin film (1) by means of an induction coil (6) which is integrated in the carrier substrate (2, 9) of the thin film (1).
5. The method according to claim 3 or 4, characterized in that the local heat input takes place by indirect heat conduction into the thin film by means of induction heating into a trigger material (10) on the carrier substrate (2).
- 25 6. The method according to claim 1 or 2, characterized in that the local heat input takes place by indirect heat conduction into the thin film (1) by means of resistance heating of resistive heating elements (11) which are arranged in the carrier substrate (2, 9) of the thin film (1).
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7. The method according to any one of claims 1 to 6, characterized in that the local heat input takes place in-situ in the deposition system (3) under an oxygen atmosphere (4).
- 5 8. The method according to any one of claims 1 to 6, characterized in that the local heat input takes place ex-situ in a heating chamber (12) under an oxygen atmosphere (4).
9. The method according to any one of claims 1 to 6, characterized in that the local heat input takes place in-situ during the deposition and a subsequent heat treatment takes place ex-situ.
- 10 10. The method according to any one of the preceding claims, characterized in that the thin film (1) is an HTS film.
11. The method according to any one of claims 1 to 9, characterized in that the thin film (1) additionally consists of further metal superconductors, A15 phases or an amorphous or crystalline alloy.
- 15 12. The method according to any one of the preceding claims, characterized in that the thin film (1) is deposited by means of PVD, CVD, ALD, PLD, ECD or by printing processes, and/or the thin film (1) has a thickness of less than 100 μm after deposition.
- 20 13. The method according to any one of the preceding claims, characterized in that the carrier substrate (2) is three-dimensionally pre-structured, and/or the carrier substrate (2) is a chip, a wafer or a panel.
14. The method according to any one of the preceding claims, characterized in that a local temperature of 200°C to 2000°C is achieved in the thin film (1) by the local heat input.
- 25 15. A device for local phase transformation and structuring of thin films of superconducting materials, said device comprising
 - a deposition system for depositing a thin film (1) of a superconducting material in a ceramic or insulating phase on a carrier substrate (2),

5 a device (6, 11) for inputting heat locally into the thin film (1), wherein regions of the thin film (1) are heated and undergo a phase transformation into a superconducting phase (8), so that regions of the superconducting phase (8) form structures embedded in the insulating phase.

16. The device according to claim 15, characterized in that the device for local heat input (6,) is also configured to heat the carrier substrate (2).
17. The device according to claim 15 or 16, characterized in that the device (6, 11) for local heat input comprises an induction coil (6) in a substrate holder (5).
18. The device according to claim 15 or 16, characterized in that the device for local heat input (6, 11) comprises an induction coil (6) in the carrier substrate (2, 9).
19. The device according to claim 17 or 18, characterized in that a trigger material (10) is arranged on the carrier substrate (2, 9) and is heated by induction heating.
20. The device according to claim 15 or 16, characterized in that the device for local heat input (6, 11, 12) comprises resistive heating elements (11) in the carrier substrate (2, 9).
21. The device according to any one of claims 15 to 20, characterized in that the device for local heat input (6, 11) is part of the deposition system (3), so that local heat input may take place in-situ in the deposition system (3).
22. The device according to any one of claims 15 to 20, characterized in that the device for local heat input (6, 11) is part of an external heating chamber (12), so that local heat input may take place ex-situ after deposition of the thin film (1).
23. The device according to any one of claims 15 to 20, characterized in that the device (6, 11) for local heat input is configured to perform the

local heat input in-situ during the deposition and to perform a second heat treatment ex-situ after the deposition.

- 5 24. The device according to any one of claims 15 to 23, characterized in that the deposition system (3) is configured to deposit a thin film (1) of an HTS.
25. The device according to any one of claims 15 to 23, characterized in that the deposition system (3) is configured to deposit additional thin films (1) of further metal superconductors, A15 phases or an amorphous or crystalline alloy.
- 10 26. The device according to any one of claims 15 to 25, characterized in that the deposition system (3) is configured to deposit a thin film (1) by means of PVD, CVD, ALD, PLD, ECD or printing processes, and/or the deposition system (3) is configured to deposit a thin film (1) with a thickness of up to 100 μm .
- 15 27. The device according to any one of claims 15 to 26, characterized in that the deposition system (3) is configured to deposit a thin film (1) on a three-dimensionally pre-structured carrier substrate (2) and/or the deposition system (3) and the device for local heat input (6, 11) are configured to process carrier substrates (2) in chip, wafer or panel size.
- 20 28. The device according to any one of claims 15 to 27, characterized in that the device (6, 11) for local heat input device is configured to reach temperatures of 200°C to 2000°C in the thin film (1).