



(51) International Patent Classification:

H04R 23/00 (2006.01) *G10K 15/04* (2006.01)
B81C 1/00 (2006.01)

(21) International Application Number:

PCT/FI2009/050956

(22) International Filing Date:

26 November 2009 (26.11.2009)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

20086138 27 November 2008 (27.11.2008) FI

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: SOUND SOURCE BASED ON THE THERMOACOUSTIC EFFECT

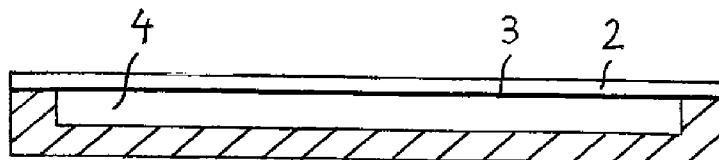


FIG. 1

(57) Abstract: A sound source based on the thermoacoustic effect comprising a substrate (1) having a front side and an opposite back side, and at least one conductor (2) on the front side of the substrate (1), said conductor (2) comprising a middle part and end parts at both ends of the middle part. Said at least one conductor (2) is thermally decoupled from the substrate (1) with a lithography process or an imprint process by etching from the front side or the back side of the substrate (1) so that the whole middle part or successive portions of the middle part of the conductor (2) is released from the substrate (1).

Sound source based on the thermoacoustic effect

TECHNICAL FIELD

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This invention relates to a sound source based on the thermoacoustic effect according to the preamble of claim 1.

BACKGROUND ART

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European patent application EP 1215936 A2 discloses a speaker including a silicon wafer, a thermal barrier layer formed by anodizing a part of the silicon wafer, and an exothermic electrode made of aluminium formed on the thermal barrier layer.

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US patent application US 2005/0201575 A1 discloses a thermally induced sound wave generating device. The device comprises a thermally conductive substrate, a heat insulating layer formed on one surface of the substrate, and a heating element thin film formed on the heat insulation layer. The heating element is in the form of an electrically driven metal film. The heat conductivity of the thermally conductive substrate is denoted α_s and its heat capacity is denoted C_s . The heat conductivity of the heat insulation layer is denoted α_i and its heat capacity is denoted C_i . It is stated that the relation of $1/100 \geq \alpha_i C_i / \alpha_s C_s$ and $\alpha_s C_s \geq 100 \cdot 10^6$ should be satisfied in this sound wave generating device.

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WO publication 03/011747 A1 discloses a method for the fabrication of suspended porous silicon membranes in the form of bridges or cantilevers and of thermal sensor devices employing these membranes. The fabrication of the suspended porous silicon membranes comprises the following steps: (a) Formation of a porous silicon layer in, at least one, predefined area of a silicon substrate, (b) Definition of etch windows around or inside said porous silicon area using stan-

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dard photolithography, (c) Selective etching of the silicon substrate, underneath the porous silicon layer, by using dry etching techniques to provide release of the porous silicon membrane and to form a cavity under said porous silicon layer. Thermal losses from the suspended-type membrane are minimized, since they
5 occur only through the supporting beams of the membrane, compared to a closed membrane where thermal losses occur along its periphery.

In L. Xiao et al, Nano. Lett. **DOI:** 10.1021/nl802750z the authors use carbon nanotube films to produce sound. The authors point out the importance of heat
10 capacity per unit area and comment that previous works on metallic films were not successful because of much higher heat capacity. The heat capacity achieved in this document is said to be below $0.01 \text{ J}/(\text{m}^2\text{K})$.

In the thermoacoustic effect, sound is produced by heating a conductor with an
15 electric signal either at half of the desired output frequency or at the output frequency. In the latter case also a direct current signal needs to be superimposed on the electric signal. Many frequencies may be combined together to produce an audio signal. Provided that the conductor is thermally insulated from the ambient temperature, in particular temperatures near room temperature, the temperature of
20 the conductor will oscillate as the square of the input signal. The conductor will exchange heat with the surrounding gas i.e. air and thus the temperature of the gas near the conductor will oscillate. This will result in oscillation of the pressure as well, thereby inducing a pressure wave, i.e. a sound wave.

25 DISCLOSURE OF INVENTION

The main characteristics of the invention are presented in the characterising part of claim 1.

30 The invention relates to a sound source based on the thermoacoustic effect comprising a substrate having a front side and an opposite back side, and at least one

conductor on the front side of the substrate, said conductor comprising a middle part and end parts at both ends of the middle part. The invention is characterised in that said at least one conductor is thermally decoupled from the substrate with a lithography process or an imprint process by etching from the front side or the back side of the substrate so that whole middle part or successive portions of the middle part of said at least one conductor is released from the substrate.

Said at least one conductor is mechanically suspended from both ends in order to thermally decouple the middle part of said at least one conductor from the substrate. This decoupling has been done by clean room fabrication techniques in a lithography process, e.g. a photo or an e-beam process or an imprint process. The thermal decoupling can be achieved via etching from the front side or the back side of the substrate in order to release the whole middle part or successive portions of the middle part of the at least one conductor from the substrate.

In another embodiment of the invention a supporting film is used under the at least one conductor. The thermal decoupling can be achieved via etching from the front side or the back side of the substrate in order to release the whole middle part or successive portions of the middle part of the at least one conductor as well as the corresponding part of the support layer from the substrate.

The release of the conductor or the conductor and the supporting film from the substrate can be made e.g. by isotropic etching of the substrate. This means that the substrate is etched from a front side by a selective method that removes the substrate material also from below of the conductor. If needed, the conductor can also be protected by an extra layer, e.g. a photoresist layer, during the isotropic etch. A possible isotropic etching method is plasma etching e.g. in reactive ion plasma. Other possible methods for the release of the conductor are Silicon-on-Insulator (SOI) techniques or embossing techniques.

The substrate can be e.g. coated or non-coated silicon. The supporting film can be e.g. silicon nitride, aluminium oxide, aluminium nitride, or silicon oxide. The conductor can be of metal e.g. aluminium, tungsten, gold, platinum or palladium. It can also be of graphite or graphene.

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A good thermal insulation and a good coupling to air of the middle part of the at least one conductor is thus achieved with a rather simple processing.

10 The sound spectrum produced with the invention may extend below and above audible frequencies. In particular, also ultrasound may be produced.

The invention could be used in e.g. a loudspeaker and an ultrasound source and arrays of them.

15 BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 shows a vertical cross section of a first embodiment of a sound source according to the invention.

20 Fig. 2 shows a vertical cross section of a second embodiment of a sound source according to the invention.

Fig. 3 shows a vertical cross section of a third embodiment of a sound source according to the invention.

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Fig. 4 shows a vertical cross section of a fourth embodiment of a sound source according to the invention.

30 Fig. 5 shows a horizontal cross section corresponding to the embodiment shown in figure 3.

Fig. 6 shows a horizontal cross section showing the conductors of fig. 3.

DESCRIPTION OF PREFERRED EMBODIMENTS

- 5 Fig. 1 shows a vertical cross section of a first embodiment of a sound source according to the invention. The sound source comprises a substrate 1 having a front side and an opposite back side, a conductor 2 on the front side of the substrate 1 and a supporting film 3 under the conductor 2. The conductor 2 has a middle part and end parts on both ends of the middle part. The middle part of the conductor 2
10 as well as the corresponding part of the support film 3 has been thermally released from the substrate 1. The thermal releasing of the conductor 2 and the support film has been done with a lithography process, e.g. a photo- or an e-beam process or an imprint process by etching from the front side or the back side of the substrate 1 so that the middle part of the conductor 2 is released from the substrate 1.
15 The middle part of the conductor 2 and the corresponding part of the support film 3 is thus surrounded by air 4 on the whole periphery of said construction, which means that said construction forms a wire bridge that is optimally coupled to the sound transmitting medium.
- 20 Fig. 2 shows a vertical cross section of a second embodiment of a sound source according to the invention. The difference in relation to the embodiment shown in fig. 1 is that the substrate 1 does not extend under the middle part of the conductor 2 and the support film 3 at all.
- 25 Fig. 3 shows a vertical cross section of a third embodiment of a sound source according to the invention. The difference in relation to the embodiment shown in fig. 1 is that the middle part of the conductor 2 and the corresponding part of the support film 3 is divided into sections. The middle part of each section of the conductor 2 and the corresponding part of the support film 3 is thermally released
30 from the substrate 1. Each section comprising the conductor 2 and the corresponding part of the support film 3 form a separate wire bridge. The construction com-

prising the conductor 2 and the support film 3 under the conductor 2 is thus divided into several wire bridges along the length of said construction. This construction gives additional mechanical support to the very thin film forming the conductor. The conductor 2 forms a succession of areas that are released from the substrate 1 and areas that are attached to the substrate 1. The total area of the part of the conductor 2 that is released from the substrate 1 is larger than the total area of the part of the at least one conductor 2 that is attached to the substrate.

Fig. 4 shows a vertical cross section of a fourth embodiment of a sound source according to the invention. The difference in relation to the embodiment shown in fig. 3 is that the substrate 1 does not extend under the middle part of each section of the conductor 2 and the corresponding part of the support film 3 at all.

Fig. 5 shows a horizontal cross section corresponding to the embodiment shown in figure 3. The conductor 2 and the support layer 3 under the conductor 2 are supported on four sides on the substrate 1.

Fig. 6 shows a horizontal cross section showing the conductors of fig. 3. The conductors 2 or the conductors 2 and the supporting layer 3 under the conductors 2 are bridged over air recesses 4, i.e. they are fastened from both ends at the substrate 1, whereas the whole periphery of the middle part of the conductor 2 and the supporting layer 3 is in contact with air, i.e. released from the substrate 1. The conductor 2 can also extend over to whole structure meaning that the end parts and a portion of the middle part of the conductor 2 are fastened to the substrate 1. The two successive released middle portions of the conductor 2 being on both sides of the supported middle portion of the conductor 2.

The embodiments shown in the figures all show a supporting layer 3 under the conductor 2. This supporting layer 3 is not compulsory and it does not benefit the performance of the invention. The purpose of the supporting layer 3 is only to protect the conductor 2 during the etching of the substrate from the front side or

the back side when the middle part of the conductor 2 is released from the substrate 1 and to give additional mechanical support to the structure.

5 The substrate 1 can be e.g. coated or non-coated silicon. The supporting film 3 can be e.g. silicon nitride, aluminium oxide or silicon oxide. The conductor 2 can be of metal e.g. aluminium, tungsten, gold, platinum or palladium. It can also be of graphite or graphene. The supporting film 3 should not be thicker than the conductor 2 so that the heat capacity per square unit of the conductor + the supporting layer is low enough.

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The conductor 2 should be as thin as possible, preferably in the order of 5 to 30 nanometer and it should sustain high temperatures. The thermal time constant of the apparatus should be as low as possible, preferably less than 10 microseconds. The conductivity and other dissipation mechanisms such as thermal radiation, and the heat capacity of the conductors 2 as well as the engagement of the conductors 2 to air determine this thermal time constant. The sound source comprises preferably a grid or network of conductors e.g. a so called spiderweb-construction or a network of parallel conductors as shown in fig. 6. As the metal layer (conductor) is very thin and thus fragile it can easily break. This means that the conductor 2 should be supported firmly. As an additional support a very thin isolating support layer 3 can be used under the conductor 2, which makes the manufacture of the device easier. The support structure and the support layer 3 must sustain elevated temperatures and they should not cause thermal stresses that might break the conductor 2.

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It is important to thermally isolate the conductor 2 from the substrate 1 to avoid heat loss. The quantities to be compared here are the heat conductivities of the substrate and the surrounding gas. The former should be as small as possible compared to the latter in order to increase the efficiency of heat transferred from the conductor to the surrounding air. The typical heat conductance of air or another gas is in the order of 0.01 W/mK while for instance silicon has a heat conductance

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of about 100 W/mK. Other substrates, in general consisting of layers, may have low values, but not typically as low as air. This shows that mechanical releasing of the middle part of the conductor 2 helps to direct the heat flow from the conductor in the desired direction, i.e. into the surrounding air.

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Also the heat capacity of the conductor 2 should be low in order for the conductor 2 temperature to follow the signal without latency. The heat capacity of the conductor 2 can be adjusted by patterning, material properties and conductor 2 dimensions. The conductor 2 should also preferably have low radiation losses, i.e. emissivity significantly below unity. The emissivity of metals is low, e.g. of aluminium Al 0.05 and of gold Au 0.04.

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It is in principle possible to construct a sound source based on one conductor 2. It is, however, more practical and efficient to use several conductors 2 in order to achieve a mechanically sustainable sound source with sufficient sound pressure. The inventors have constructed several versions of sound sources according to the invention using between 6,000 and 233,000 conductors. Each conductor was 50 to 200 micrometers long, 3 micrometers wide, and 30 nanometers thick. The end parts of the conductors were clamped to supports to form "air bridges" hovering a few microns above the substrate underneath. It seems advisable to have at least two, preferably at least 100 and most preferably a great number of conductors in the sound source according to the invention.

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CLAIMS

1. A sound source based on the thermoacoustic effect comprising a substrate (1) having a front side and an opposite back side, and at least one conductor (2) on the front side of the substrate (1), said conductor (2) comprising a middle part and end parts at both ends of the middle part, **characterised** in that said at least one conductor (2) is thermally decoupled from the substrate (1) with a lithography process or an imprint process by etching from the front side or the back side of the substrate (1) so that the whole middle part or successive portions of the middle part of said at least one conductor (2) is released from contact with the substrate (1).
2. A sound source according to claim 1, **characterised** in that the sound source further comprises a supporting film (3) under the conductor (2), whereby said at least one conductor (2) is thermally decoupled from the substrate (1) by a lithography process or an imprint process by etching from the front side or the back side of the substrate (1) so that the whole middle part or successive portions of the middle part of said at least one conductor (2) and the corresponding part of the supporting film (3) under said at least one conductor (2) is released from contact with the substrate (1).
3. A sound source according to claim 1 or 2, **characterised** in that the at least one conductor (2) forms a succession of areas that are released from the substrate (1) and areas that are attached to the substrate (1), the total area of the part of said at least one conductor (2) that is released from the substrate (1) being larger than the total area of the part of the at least one conductor (2) that is attached to the substrate (1).
4. A sound source according to any one of claims 1 to 3, **characterised** in that the sound source comprises at least two conductors (2).

5. A sound source according to any of claims 1 to 4, **characterised** in that the lithography process is a photo or e-beam process.

6. A sound source according to any of claims 1 to 5, **characterised** in that the
5 substrate (1) is silicon.

7. A sound source according to any of claims 1 to 6, **characterised** in that the conductor (2) is made of aluminium, tungsten, gold, platinum, palladium, graphite or graphene.

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8. A sound source according to any of claims 2 to 7, **characterised** in that the supporting film (3) is silicon nitride, aluminium oxide, aluminium nitride, or silicon oxide.

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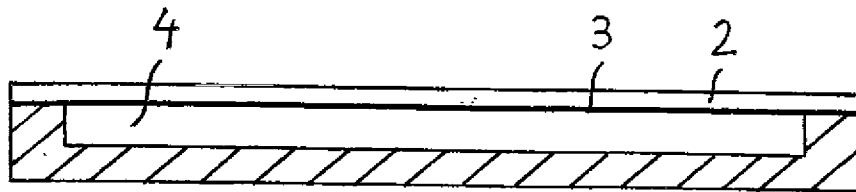


FIG. 1

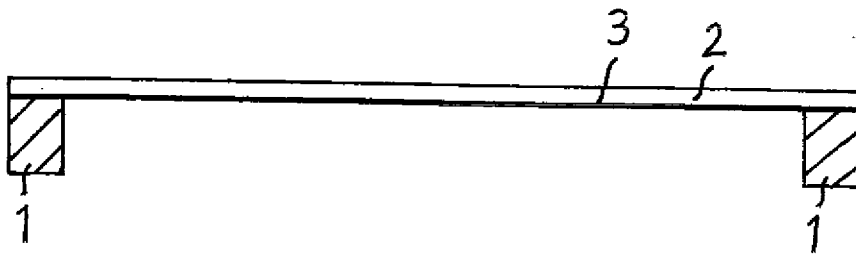


FIG. 2

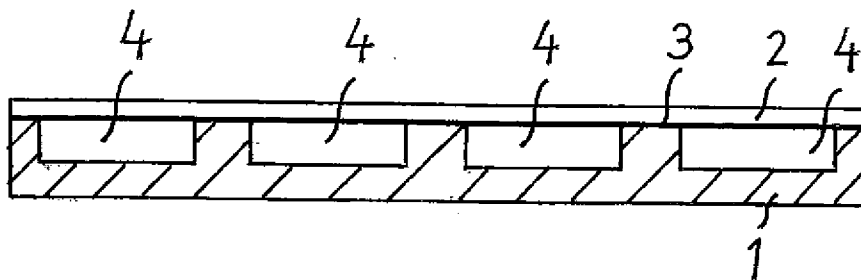


FIG. 3

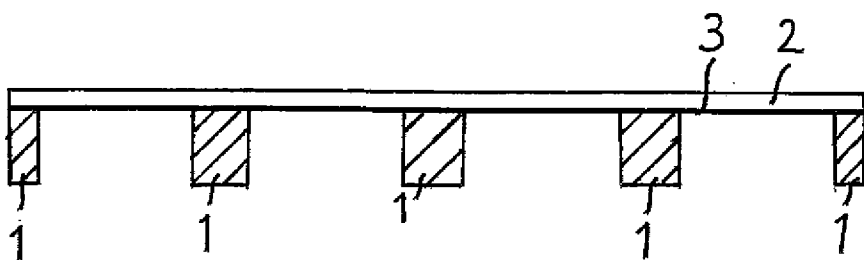


FIG. 4

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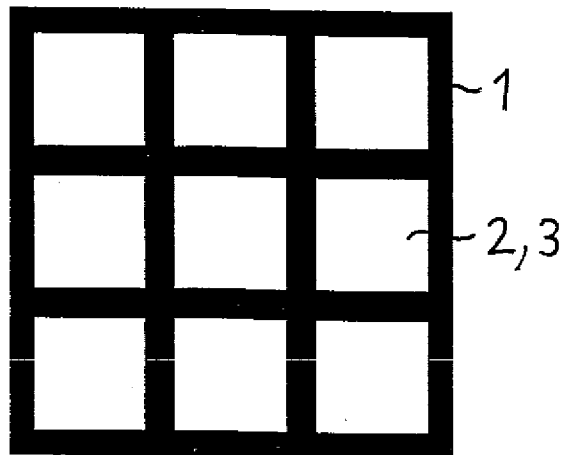


FIG. 5

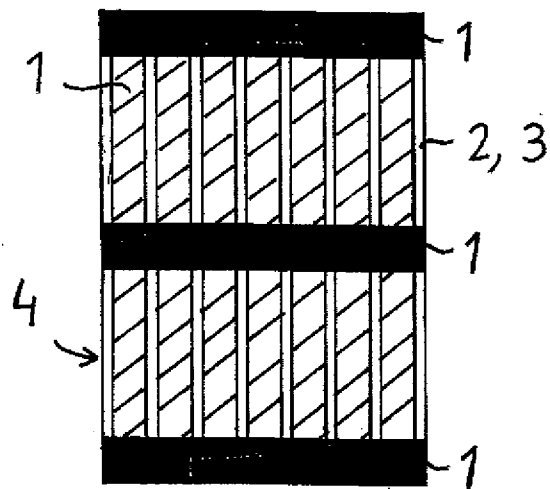


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2009/050956

A. CLASSIFICATION OF SUBJECT MATTER

See extra sheet

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)

IPC: H04R, B81C, G10K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
FI, SE, NO, DK

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

EPO-Internal, WPI, IEEEExplore, COMPDX, EMBASE, INSPEC, MEDLINE, XPAIP, XPIOP, XPI3E, XPRD

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Arnold HD, Crandall IB, The thermophone as a precision source of sound, Phys. Rev. 10, pp, 22-38, 1917 page 23, fig.1	1-8
A	US 2006220499 A1 (IKEHASHI T) 05 October 2006 (05.10.2006) paragraph [0048]	1-8
A	US 2008238257 A1 (KAWAKUBO T et al.) 02 October 2008 (02.10.2008) paragraph [0049]	1-8
A	Shinoda H, et.al, Thermally induced ultrasonic emission from porous silicon, Nature vol. 400, pp. 853-855, 26 August 1999 pages 853-854, figure 1	1-8
A	US 2007176498 A1 (SUGIURA M et al.) 02 August 2007 (02.08.2007) Whole document	1-8



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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

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"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

"&" document member of the same patent family

Date of the actual completion of the international search

24 February 2010 (24.02.2010)

Date of mailing of the international search report

05 March 2010 (05.03.2010)

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2009/050956

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2006137008 A2 (KONINKL PHILIPS ELECTRONICS NV) 28 December 2006 (28.12.2006) Whole document	1-8

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI2009/050956

CLASSIFICATION OF SUBJECT MATTER

Int.Cl.

H04R 23/00 (2006.01)

B81C 1/00 (2006.01)

G10K 15/04 (2006.01)