(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 September 2017 (14.09.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/153773 A1

(51) International Patent Classification:
H01H 59/00 (2006.01) *H01H 1/00* (2006.01)

(21) International Application Number:
PCT/GB2017/050655

(22) International Filing Date:
10 March 2017 (10.03.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
1604254.1 11 March 2016 (11.03.2016) GB

(71) Applicant: **THE UNIVERSITY OF BRISTOL** [GB/GB]; Senate House, Tyndall Avenue, Bristol Bristol BS8 1TH (GB).

(72) Inventors: **RANA, Sunil**; The University of Bristol, Senate House, Tyndall Avenue, Bristol Bristol BS8 1TH (GB). **PAMUNUWA, Dinesh**; The University of Bristol, Senate House, Tyndall Avenue, Bristol Bristol BS8 1TH (GB). **BOODHOO, Liam Anand**; The University of Bristol, Senate House, Tyndall Avenue, Bristol Bristol BS8 1TH (GB). **CHONG, Harold Meng Hoon**; The Universtiy of Bristol, Senate House, Tyndall Avenue, Bristol Bristol BS8 1TH (GB).

(74) Agents: **WITHERS & ROGERS LLP** et al.; 4 More London Riverside, London Greater London SE1 2AU (GB).

(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, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, 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, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, 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, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: ELECTROMECHANICAL RELAY DEVICE

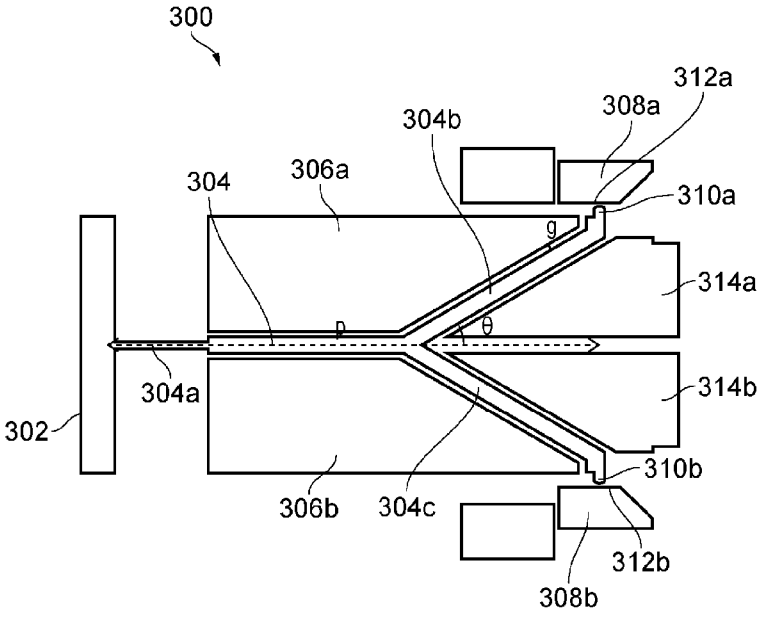


FIG. 3

(57) Abstract: A electromechanical relay device (100) comprising a source electrode (102), a beam (104) mounted on the source electrode at a first end and electrically coupled to the source electrode; a first drain electrode (112) located adjacent a second end of the beam, wherein a first contact (110) on the beam is arranged to be separated from a second contact (112) on the first drain electrode when the relay device is in a first condition; a first gate electrode (106arranged to cause the beam to deflect,to electrically couple the first contact and the second contact such that the device is in a second condition; and wherein the first and second contacts are each coated with a layer of nanocrystalline graphite.

WO 2017/153773 A1

Published:

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

Electromechanical relay device

Background

Transistors are widely used in integrated circuits. However, transistors only have a limited range of operating conditions. High or low temperatures or ionising radiation can all change the way their constituent semiconductor materials will behave and seriously affect device operation. For example, a commercially available field programmable gate array (FPGA) designed for extreme environments can generally withstand up to 125°C and 300 krad absorbed dose of radiation.

It is desirable, in some industries, to move electronic sensors closer to high temperature environments, for example to improve control system reaction time and reduce weight of cabling.

Nanoelectromechanical relays are electrically actuated mechanical switches in which a cantilevered or doubly-clamped beam attached to a source electrode is deflected towards a drain electrode using an electric field created from the application of a voltage difference between a gate electrode and the beam. A nanoelectromechanical device can withstand greater than 100 Mrad of radiation dose without additional radiation-hardened packaging and can operate at over 200°C. However, known nanoelectromechanical relay devices are not practical for use in most applications as they can only undergo a very limited number of switching cycles before failure.

Summary

According to a first aspect of the invention, there is provided an electromechanical relay device comprising a source electrode, a beam, which can be mounted on the source electrode at a first end and is electrically coupled to the source electrode; a first drain electrode located adjacent a second portion of the beam, wherein a first contact on the second portion of the beam is arranged to be separated from a second contact on the first drain electrode when the relay device is in a first condition; a first gate electrode arranged

to cause the beam to deflect, to electrically couple the first contact and the second contact such that the device is in a second condition; and wherein the first and second contacts are each coated with a layer of nanocrystalline graphite (NCG).

The beam can be attached to the source at the first end in a cantilevered fashion, and the first contact can be located at a second end of the beam, opposite to the first end. Alternatively, the beam can be additionally fixed at a second end, opposite to the first end and the first contact can be located on the beam between the first and second ends. The skilled person will appreciate that other arrangements of the source, beam and drain electrodes can be used.

The gate electrode may be located alongside the beam such that it imparts an electrostatic force directly on the beam, causing the beam to deflect. Alternatively the gate electrode may impart an electrostatic force that indirectly causes the beam to deflect.

A key reason for the failure of known electromechanical devices after a small number of switching cycles is due to the contact materials of the beam and drain electrodes, which degrade after each cycle, causing electrical resistance between the beam and the drain to increase, or the contacts to stick in place due to micro-welding, both of which can make the switch unusable.

Stiction is also a major failure mode in known electromechanical relays, which primarily occurs due to the Van der Waals forces present between the contact area of the beam and the contact area of the drain. In known electromechanical relays, these contact areas are often minimised in order to reduce the stiction. However, minimising the contact area between the beam and the drain increases the electrical resistance between these components which is also undesirable.

The inventors have found that coating the first and second contacts of electromechanical relays with NCG enables hot switching of the electromechanical relays with a significant reduction in instances of failure of the relays due to stiction or micro-welding between the beam and the drain, whilst still maintaining a low contact resistance. Thus, the electromechanical relay device according to the first aspect of the invention can perform

many operational cycles without failure, thus showing reliability sufficient for practical use.

The electromechanical relay may be a micromechanical relay, wherein at least one dimension of the relay is between 1 and 1000 μm.

The electromechanical relay may be a nanoelectromechanical relay, wherein at least one dimension of the relay is between 1 and 1000 nm.

In some embodiments, the electromechanical relay may have a footprint area of 1 μm^2 to 20 μm^2.

The use of NCG is particularly advantageous for nano and micro electromechanical relays, as for electromechanical relays of these sizes, stiction and microwelding are particularly significant failure modes.

In some embodiments a greater area of the surface of the electromechanical relay may be coated with NCG. In some embodiments the whole surface area of the electromechanical relay may be completely coated with NCG.

The inventors have found that coating the electromechanical relay with NCG also improves the stability of the contacting electrodes of the electromechanical relay, enabling the relay to be stored in ambient conditions at room temperature without the need for hermetic packaging.

The NCG layer can be at least 10nm in thickness. The NCG layer can be between 10 nm and 80 nm in thickness on each surface.

The electromechanical relay can be fabricated with a conductive thin-film on the surface of the device, including the contact area, underneath the NCG layer. The NCG layer can then be deposited on top of the conductive layer.

Including a conductive layer underneath the NCG layer can reduce the resistance between the beam and the drain when they are in contact.

The conductive layer can be formed in a variety of ways, including but not limited to, deposition of a conductive film comprising metal, deposition of a conducting film comprising an oxide, or formation of a metal silicide.

The electromechanical relay device can further comprise a second gate and a second drain electrode, wherein the first gate is located along one side of the beam and the second gate is located along an opposing side of the beam; and wherein the beam has a forked section comprising a first and a second branch; and one or more auxiliary gates are located between the first and second branches, such that the beam is arranged to be separated from the first and second drain electrodes when the device is in a first state; the first gate and an auxiliary gate being arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the first branch and the first drain electrode when the device is in the second state; and the second gate and an auxiliary gate being arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the second branch and the second drain electrode when the device is in the third state.

This geometry is advantageous as it enables bi-directional operation of the relay, whilst only requiring a single lithography step for the relay definition. Furthermore, including an auxiliary gate is advantageous as this increases the electrostatic actuation force, enabling a lower voltage to be used to deflect the beam.

The beam may comprise a hinge located between the forked section and the first end.

The hinge can be, for example a section of the beam having a narrower width than the main body of the beam, such that the stiffness of the beam is reduced at the hinge. Alternatively the hinge can be formed by reducing the stiffness of the beam between the forked section and the first end using other methods, for example by using a serpentine geometry.

Including a hinge in the beam is advantageous as the hinge acts as a stress concentration region, which minimises stress and deformation across the rest of the beam. Thus the beam

is less likely to collapse onto the gate, which can be a common problem for electromechanical relays with known geometries.

Preferably, the fork angle (the angle between the unbranched and branched sections of the beam) may be between 30° and 45°.

According to a second aspect of the invention, there is provided a method for producing an electromechanical relay comprising patterning the silicon device layer using lithography, releasing the relay beam by etching an underlying silicon dioxide sacrificial layer and critical point drying, and blanket depositing a layer of NCG onto the device silicon by plasma-enhanced chemical vapour deposition.

A conductive layer may be deposited onto the device silicon prior to deposition of the NCG.

According to a third aspect of the invention there is provided an electromechanical relay device comprising a source electrode, a beam mounted on the source electrode at a first end that is electrically coupled to the source electrode, first and second gates and first and second drain electrodes; wherein the first gate is located along one side of the beam and the second gate is located along an opposing side of the beam; and wherein the beam has a forked section comprising a first and a second branch; and one or more auxiliary gates are located between the first and second branches, such that the beam is arranged to be separated from the first and second drain electrodes when the device is in a first state; the first gate and an auxiliary gate being arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the first branch and the first drain electrode when the device is in the second state; and the second gate and an auxiliary gate being arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the second branch and the second drain electrode when the device is in the third state.

It will be appreciated that features of the first aspect can also apply analogously to the third aspect.

Brief description of the drawings

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of an electromechanical relay device according to a first embodiment in a first state;

Figure 2 is a schematic diagram of the electromechanical relay device of Figure 1, in a second state;

Figure 3 is a schematic diagram of an electromechanical relay device according to a second embodiment; and

Figure 4 is a schematic diagram of a method of producing the electromechanical relay device of Figure 3.

Detailed description

In Figure 1, an electromechanical relay device according to a first embodiment is shown generally at 100. The electromechanical relay device has a source electrode (source) 102, which is an input terminal, connected to a voltage source (not shown). A cantilever beam 104 is attached at one end to the source and has a free end at an opposite end of the beam 104. The beam 104 may be a separate element which is attached to the source 102 by any suitable means. Preferably, the beam can be integrally formed as part of the source 102. The electromechanical relay 100 further includes a gate 106 which is an actuation terminal, located alongside the beam 104, on a first side of the beam and is connected to a voltage source. The electromechanical relay device further includes a drain electrode (drain) 108, which is an output terminal, located on the first side of the beam, in line with the free end of the beam. The electromechanical relay device is made of silicon. Figure 1 shows the electromechanical relay device in a first state in which the beam 104 and the drain 108 are separated by an air gap. In the embodiment shown in Figure 1, the first state is an "off"

state. In the embodiment shown in Figure 1, the source 102, beam 104, drain 108 and gate 106 are formed from silicon.

Figure 2 shows an electromechanical relay device in a second state, in which the beam 104 contacts the drain 108. In the embodiment shown in Figure 2, the second state is an "on" state. In order to cause the electromechanical relay device to transition from the first state to the second state, a voltage differential is applied between the beam 104 and the gate 106, causing the beam 104 to bend towards the gate 106, until eventually, a first contact 110 located on the free end of the beam 104 makes contact with a second contact 112 located on the drain 108. The voltage at which the beam 104 is bent sufficiently to come into contact with the drain 108 is known as the "pull in" voltage. If the voltage applied between the beam 104 and the gate 106 is subsequently lowered, the beam 104 will separate from the drain 108 and the electromechanical relay 100 will return to the first state. The voltage at which the beam 104 separates from the drain 108 is known as the "pull out" voltage, which is a lower voltage than the pull in voltage.

The electromechanical relay 100 is coated with a 50nm layer of NCG. However, in some embodiments, the layer of NCG may be between 10 nm and 80 nm. In some embodiments, the electromechanical relay may not be completely coated with NCG, although the first contact 110 and the second contact 112 at least are each coated with NCG.

It will be appreciated that other arrangements of the source, drain and gate electrodes can be used in embodiments of the invention. For example, in some embodiments, the beam may be doubly-clamped and the first contact area may be located between ends of the beam.

In some embodiments, the electromechanical relay can comprise a second gate located alongside the beam on a second side of the beam, and a second drain, located on the second side of the beam in line with the free end of the beam. In these embodiments, the electromechanical relay device is bi-directional as the beam can be pulled in a first direction by the first gate to contact the first drain or can be pulled in a second direction by the second gate to contact the second drain.

In Figure 3, an electromechanical relay device according to a second embodiment is shown generally at 300. The electromechanical relay device comprises a source 302, with a beam 304 attached to the source at a first end. The beam 304 and source 302 are integrally formed as a single unit.

At the first end, the width of the beam 304 is narrower than the main body of the beam 304, forming a hinge 304a. At a second end, opposite to the first end, the beam 304 has a forked section, in which the beam 304 is split into two branches, 304b and 304c. In the embodiment shown in Figure 3, the fork angle θ is 30°. However, in some embodiments another fork angle can be used. Preferably the fork angle is between 30° and 45°.

The electromechanical relay 300 comprises a first gate 306a which is located along a first side of the beam 304, extending alongside an outer edge of the first branch 304b; and a second gate 306b, which is located along a second side of the beam 304, extending alongside an outer edge of the second branch 304c.

The electromechanical relay 300 further includes a first drain 308a, located adjacent to a contact 310a at a free end of the first branch 304b, and a second drain 308b, located adjacent to a contact 310b at a free end of the second branch 304c.

The electromechanical relay 300 also includes a first auxiliary gate 314a, located alongside an inner edge of the first branch 304b, and a second auxiliary gate 314b, located alongside an inner edge of the second branch 304c.

In the embodiment shown in Figure 3, the source 302, beam 304, drains 308a, 308b and gates 306a, 306b, 314a, 314b are formed from silicon.

The electromechanical relay 300 operates in a similar manner as described with respect to Figure 1. However, electromechanical relay 300 is operable to transition between three different states. In the first state, both of the first and second branches 304b, 304c are separated from the first and second drains 308a, 308b. To transition the electromechanical relay to a second state, a differential voltage is applied between the branch 304 and the gates 306a and 314b in a first direction, such that the beam 304 is pulled towards the first

gate 306a and the first contact 310a on the free end of the first branch 304b makes contact with a second contact 312a on the first drain 308a. To transition the electromechanical relay 300 to a third state, a differential voltage is applied between the branch 304 and the gates 306b and 314a in a second direction, such that the beam 304 is pulled towards the second gate 306b and a third contact 310b on the free end of the second branch 304c makes contact with a fourth contact 312b on the free end of the second drain 308b.

The electromechanical relay 300 is coated with a 50nm layer of NCG. However, in some embodiments, the layer of NCG can be between 10nm and 80 nm. In some embodiments, the electromechanical relay may not be completely coated with NCG, although the first, second, third and fourth contacts are each coated with a layer of NCG.

In the embodiment shown in Figure 3, the horizontal projection, p, of the beam length is between 90 and 200 μm. The gate-to-beam actuation gap, g, is between 1 and 2 μm. However, it will be appreciated that all of the embodiments of the invention can be scaled, and some embodiments can have different dimensions. In some embodiments, the electromechanical relay device can have a footprint of 1 μm^2 to 20 μm^2. In some embodiments the electromechanical relay device can have an overall footprint of 3 μm x 2 μm, or of 6 μm^2.

The use of an NCG coating on the contacts of the device is particularly advantageous for nano and micro electromechanical relays, as for electromechanical relays of these sizes, stiction and microwelding are particularly significant failure modes.

In Figure 4, a method of producing the electromechanical relay device of Figure 3 is shown generally at 400. The electromechanical relay device of Figure 3 has been fabricated from silicon-on-insulator (SOI) wafers. At step 402, a 60nm thick layer of nickel N, to be used as a hard mask, is deposited on the device silicon ds layer using evaporation. A layer of buried oxide BO separates the device silicon DS from an underlying layer of handle silicon HS. At step 404, the nickel layer is patterned using optical lithography (for example, using S1805 positive photoresist) and a timed nickel wet etch. At step 406, the device silicon layer is etched using SF_6/O_2 inductively coupled plasma (ICP). Once the relay pattern is transferred to the device silicon layer, the nickel hard mask is stripped off using a wet etch

at step 406, and the wafer is diced and the relay beam is released using a buffered HF etch of BO followed by critical point drying. Optionally, at step 408, a 20 nm thick layer of metal such as titanium Ti is sputtered on to the device silicon. Finally, at step 410, a 50 nm thick layer of NCG is blanket deposited on device by plasma-enhanced chemical vapour deposition (PEVCD), for example, using an Oxford Instruments Nanofab 1000 Agile PECVD tool.

It will however be appreciated that an electromechanical relay according to embodiments of the invention can be produced in other ways; for example, different masking materials may be used, such as photoresist only, or silicon dioxide as a hard mask; different lithography methods such as electron-beam (e-beam) lithography may be used with compatible masking materials (e-beam photoresists); different conductive films, including, but not limited to, metals such as Pt, Au, W, conductive oxides such as ITO and silicides may be used; the air gap between the beam and gate electrode, which is defined lithographically in the above process, may be defined using a silicon dioxide sacrificial layer instead.

Embodiments of the application can be used advantageously in a number of applications. For example, in the aerospace industry, aircraft electronics experience 500 times the cosmic radiation at ground level, which is a level of radiation that is easily withstood by electromechanical relays with no additional radiation hardening required. There is also a requirement for electronic components for fuel control systems, which need to operate at around 200°C.

In automotive applications, there is a requirement to increase fuel efficiency and reduce emissions (CO_2 and NOx). Placing electronics and sensors closer to high temperature areas can address this by improving control systems response and reducing weight. For engines that include a turbocharger, exhaust temperatures can exceed 1000°c, so there is a requirement for electronic components located near to these systems to withstand high temperatures.

Another example of an application in which the invention can be used advantageously is in sensors for domestic boilers, for example carbon monoxide and carbon dioxide sensors, which are required to withstand temperatures up to 225°c.

Oil and gas drills require sensors at the tip of the drill to monitor CO_2, H_2S, water and temperature. Communication with the drill is of very limited bandwidth, requiring much processing to be done at the tip of the drill. Therefore a number of electronic components are located at the tip of the drill. The environment at the drill tip can have a temperature of 170°C.

Electronic components in nuclear reactors need to withstand very high levels of radiation and high temperatures, and electromechanical relays are able to operate under absorbed levels of gamma radiation and heavy ion fluences that are two orders of magnitude higher than conventional transistors, at a temperature of over 200°C. Thus they have potential in civilian power-generation applications as well as defence applications such as electronic components in nuclear submarines, drones in nuclear disaster areas and missile heads.

New computing paradigms such as the internet of things demand extreme energy efficiency in microprocessors, for example to form autonomous remote sensing nodes that are powered by energy scavenging from natural phenomena. Electromechanical relays have zero leakage current and thus eliminate one of the main challenges in realising such systems.

In the applications mentioned above, the electromechanical relay device of the invention can provide advantages due to its ability to withstand high temperature and ionising radiation, and due to its having zero quiescent current in the off-state. It will be appreciated that the electromechanical relay device can be used advantageously in other applications, in particular in applications where high temperatures, and/or high levels of radiation are present, and/or where extreme energy efficiency is a requirement.

Although the invention has been described above with reference to one or more preferred embodiments, it will be appreciated that various changes or modifications may be made without departing from the scope of the invention as defined in the appended claims. The

word "comprising" can mean "including" or "consisting of" and therefore does not exclude the presence of elements or steps other than those listed in any claim or the specification as a whole. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

5

Claims

1. An electromechanical relay device comprising:

a source electrode;

a beam electrically coupled to the source electrode;

a first drain electrode located adjacent a first contact on the beam, wherein the first contact is arranged to be separated from a second contact on the first drain electrode when the relay device is in a first condition; and

a first gate electrode arranged to cause the beam to deflect, to electrically couple the first contact and the second contact such that the device is in a second condition,

wherein the first and second contacts are each coated with a layer of nanocrystalline graphite.

2. An electromechanical relay device according to claim 1, wherein the majority of the electromechanical relay device is coated with a layer of nanocrystalline graphite.

3. An electromechanical relay device according to claim 1 or 2 further comprising a conductive layer provided underneath the nanocrystalline graphite layer.

4. An electromechanical relay device according to any preceding claim wherein the beam and the source electrode are integrally formed as a single unit.

5. An electromechanical relay device according to any previous claim, further comprising a second gate electrode and a second drain electrode, wherein the first gate electrode is located along one side of the beam and the second gate electrode is located along an opposing side of the beam; and

wherein the beam has a forked section comprising a first and a second branch; and

one or more auxiliary gate electrodes are located between the first and second branches, such that the beam is arranged to be separated from the first and second drain electrodes when the device is in a first state;

the first gate electrode and an auxiliary gate electrode are arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the first branch and the first drain electrode when the device is in the second state; and

the second gate electrode and an auxiliary gate electrode are arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the second branch and the second drain electrode when the device is in the third state.

6. An electromechanical relay device according to claim 5, further comprising one or more auxiliary gate electrodes located between the branches of the beam.

7. An electromechanical relay device according to any preceding claim wherein the beam comprises a hinge located between the forked section and the first end.

8. An electromechanical relay device according to any preceding claim, wherein the electromechanical relay device is a nanoelectromechanical relay device.

10. A method for producing an electromechanical relay device comprising evaporating a nickel layer onto a layer of device silicon of a silicon wafer, patterning the nickel layer and the device silicon using lithography, striping the nickel and releasing the relay beam by etching and critical point drying, and blanket depositing a layer of nanocrystalline graphite onto the device silicon by plasma-enhanced chemical vapour deposition.

11. A method according to claim 8, further comprising depositing a conductive layer onto the device silicon prior to deposition of the nanocrystalline graphite.

Claims

1. An electromechanical relay device comprising:

a source electrode;

a beam electrically coupled to the source electrode;

a first drain electrode located adjacent a first contact on the beam, wherein the first contact is arranged to be separated from a second contact on the first drain electrode when the relay device is in a first condition; and

a first gate electrode arranged to cause the beam to deflect, to electrically couple the first contact and the second contact such that the device is in a second condition,

wherein the first and second contacts are each coated with a layer of nanocrystalline graphite.

2. An electromechanical relay device according to claim 1, wherein the majority of the electromechanical relay device is coated with a layer of nanocrystalline graphite.

3. An electromechanical relay device according to claim 1 or 2 further comprising a conductive layer provided underneath the nanocrystalline graphite layer.

4. An electromechanical relay device according to any preceding claim wherein the beam and the source electrode are integrally formed as a single unit.

5. An electromechanical relay device according to any previous claim, further comprising a second gate electrode and a second drain electrode, wherein the first gate electrode is located along one side of the beam and the second gate electrode is located along an opposing side of the beam; and

wherein the beam has a forked section comprising a first and a second branch; and

one or more auxiliary gate electrodes are located between the first and second branches, such that the beam is arranged to be separated from the first and second drain electrodes when the device is in a first state;

the first gate electrode and an auxiliary gate electrode are arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the first branch and the first drain electrode when the device is in the second state; and

the second gate electrode and an auxiliary gate electrode are arranged to impart an electrostatic force on the beam to deflect the beam to electrically couple the second branch and the second drain electrode when the device is in the third state.

6. An electromechanical relay device according to claim 5, further comprising one or more auxiliary gate electrodes located between the branches of the beam.

7. An electromechanical relay device according to any preceding claim wherein the beam comprises a hinge located between the forked section and the first end.

8. An electromechanical relay device according to any preceding claim, wherein the electromechanical relay device is a nanoelectromechanical relay device.

10. A method for producing an electromechanical relay device, the method comprising:

providing a silicon wafer, having a device silicon layer and an underlying silicon dioxide layer;

patterning the device silicon layer using lithography to form a beam;

releasing the beam by etching the underlying silicon dioxide layer and critical point drying; and

blanket depositing a layer of nanocrystalline graphite onto the device silicon layer by plasma-enhanced chemical vapour deposition.

11. A method according to claim 8, further comprising depositing a conductive layer onto the device silicon layer prior to deposition of the nanocrystalline graphite.

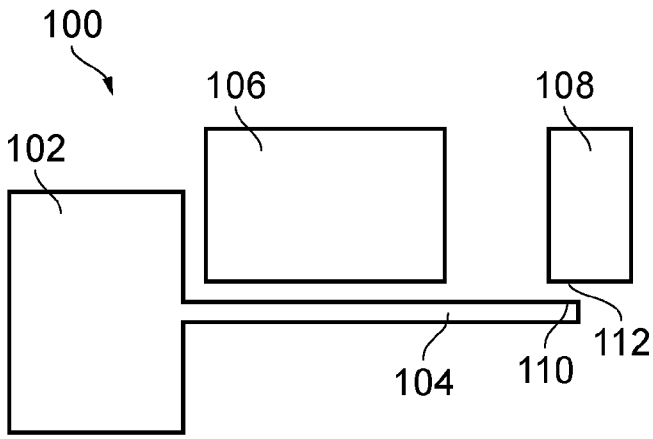


FIG. 1

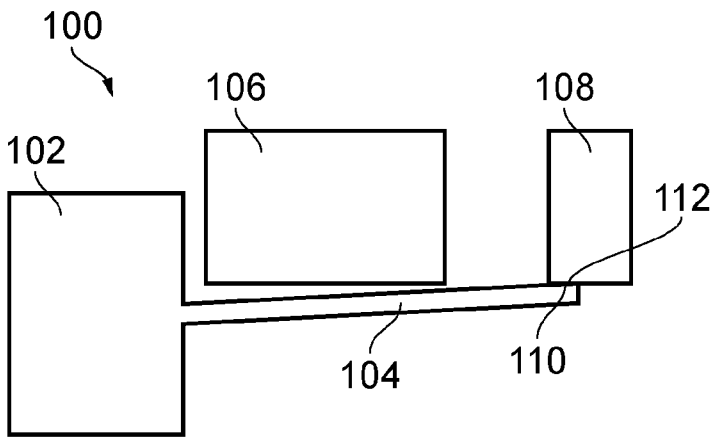


FIG. 2

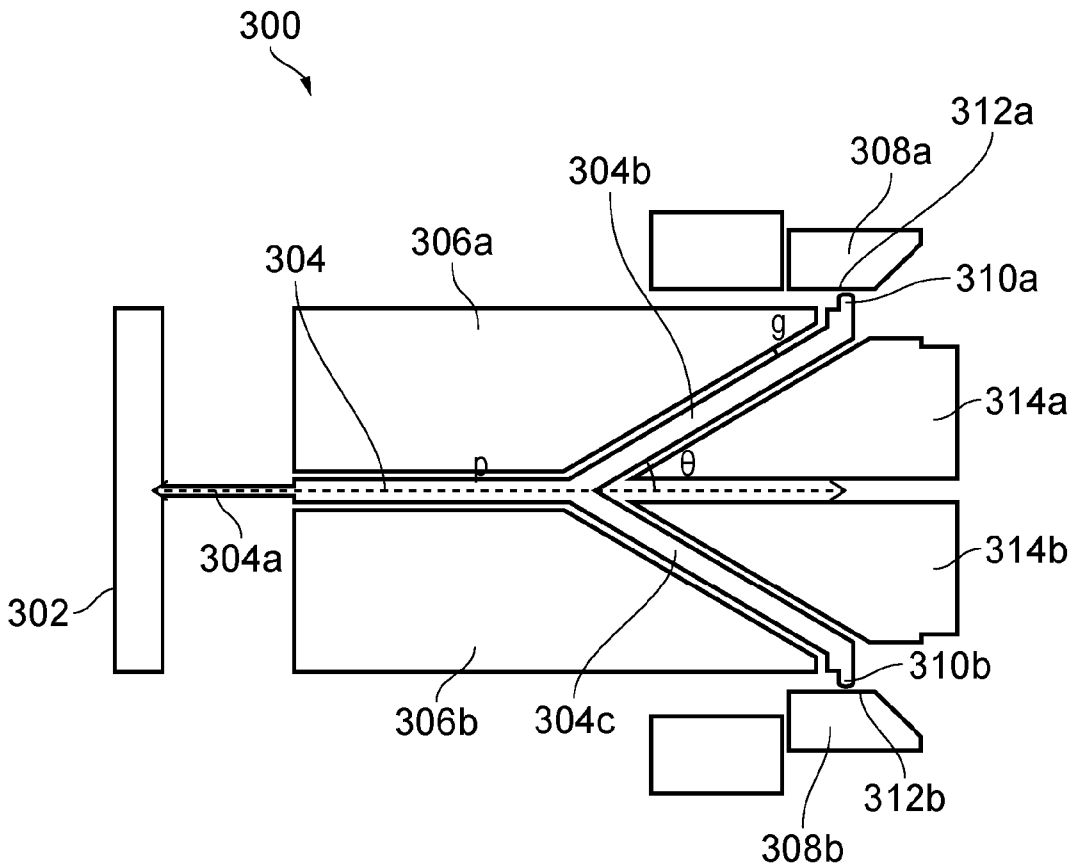

300
312a
308a
304b
306a
304
310a
g
314a
p
θ
304a
314b
302
310b
306b
304c
312b
308b

FIG. 3

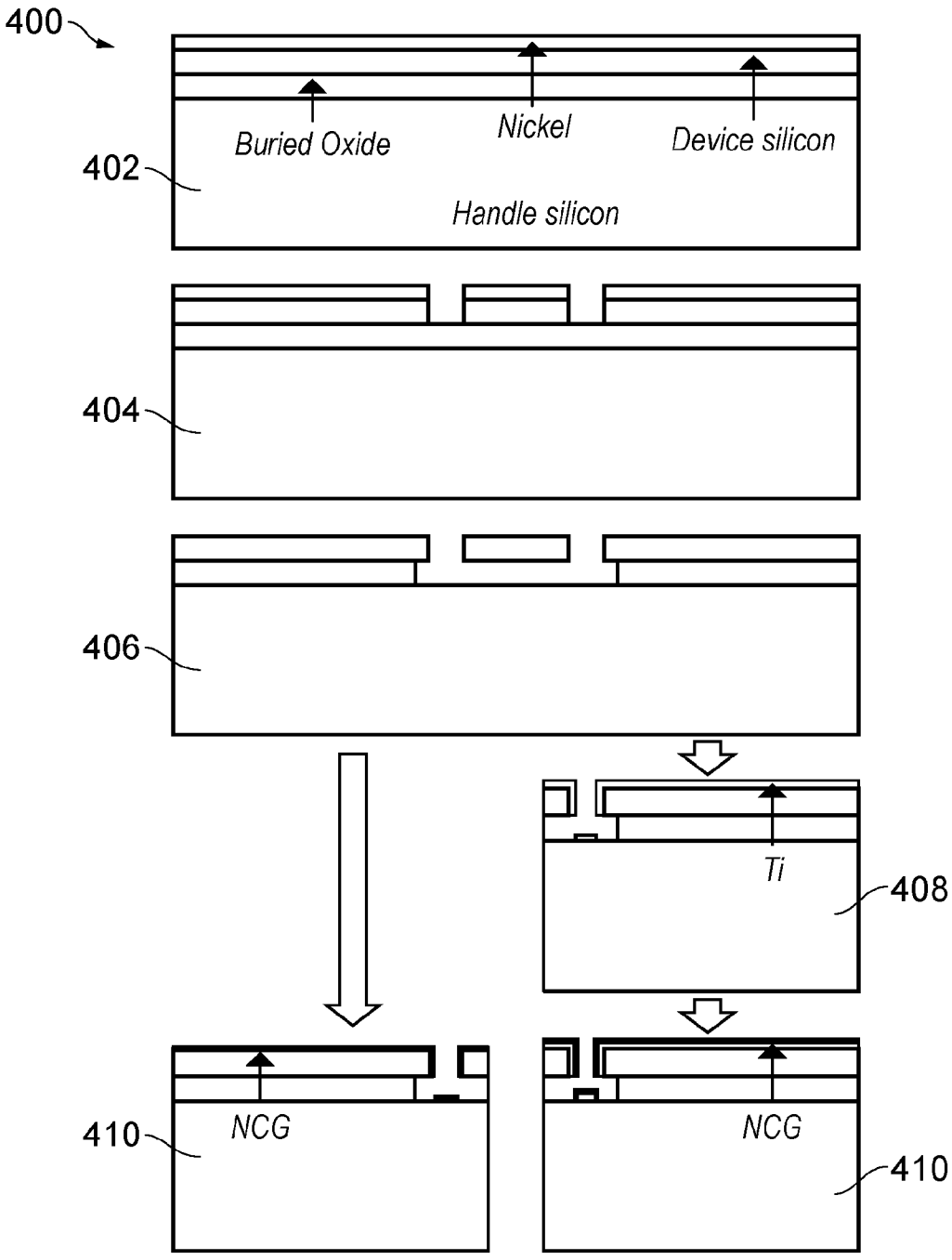

400
Buried Oxide
Nickel
Device silicon
402
Handle silicon
404
406
Ti
408
NCG
410
NCG
410

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/050655

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01H59/00
ADD. H01H1/00

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)
H01H

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 practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 1 430 498 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]) 23 June 2004 (2004-06-23)	1-8
A	pages 3-4; figures 1-4	10,11

Y	CN 103 177 904 A (UNIV TSINGHUA) 26 June 2013 (2013-06-26) pages 2-5; figures 1-2	1-8,10, 11

Y	EP 2 743 955 A1 (OMRON TATEISI ELECTRONICS CO [JP]) 18 June 2014 (2014-06-18)	10,11
A	pages 8-12; figures 1-22	1-8

Y	WO 2005/117051 A1 (YOKOHAMA TLO COMPANY LTD [JP]; UKYO TSUYOSHI [JP]; ISHIKAWA KOJI [JP];) 8 December 2005 (2005-12-08)	5,6
A	abstract; figures 1-17	1-4,7,8, 10,11

	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 May 2017	13/06/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Rucha, Johannes

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/050655

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 8 519 809 B1 (FU YEE-CHUNG [US]) 27 August 2013 (2013-08-27) columns 1-5; figures 1-3 -----	1-11

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2017/050655

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 1430498 A1	23-06-2004	EP 1430498 A1	23-06-2004
		JP 2005504415 A	10-02-2005
		KR 20040053127 A	23-06-2004
		US 2003059973 A1	27-03-2003
		WO 03028058 A1	03-04-2003
CN 103177904 A	26-06-2013	NONE	
EP 2743955 A1	18-06-2014	EP 2743955 A1	18-06-2014
		JP 5720485 B2	20-05-2015
		JP 2013041733 A	28-02-2013
		TW 201318957 A	16-05-2013
		US 2014202838 A1	24-07-2014
		WO 2013024658 A1	21-02-2013
WO 2005117051 A1	08-12-2005	NONE	
US 8519809 B1	27-08-2013	NONE	