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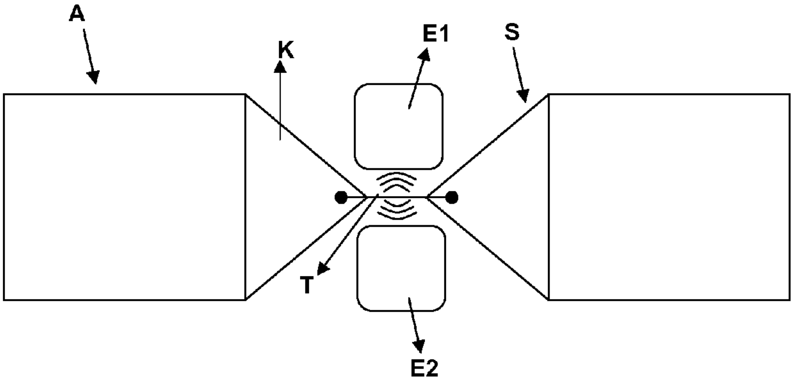

Figure – 2

(57) **Abstract**: The present invention discloses an oscillator having an adjustable oscillating frequency, as well as a method for producing this oscillator. Said oscillator comprises a nanomechanical resonator (T); a MEMS- based actuator element (A) to which the resonator (T) is coupled from one end thereof; a feedback means (S) measuring the stress value of the resonator (T) and transmitting this measured value to the actuator element (A); an actuator electrode (El) setting the resonator in vibration by the electrical field it applies; and a reading electrode (E2) generating a signal output at a certain frequency based on the vibrations of the resonator (T). A method according to the present invention, in turn, comprises the steps of producing a resonator (T) such that one of its ends is coupled to the actuator element (A) and its other end to the feedback means (S), and integrating the actuator electrode (El) and the reading electrode (E2) into the structure of the resonator (T), actuator element (A), and feedback means (S) in a monolithic manner.

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DESCRIPTION

A TUNABLE NANOMECHANICAL OSCILLATOR AND A PRODUCTION METHOD THEREOF

Field of Invention

The present invention relates to a tunable oscillator based on a nanomechanical resonator of which the natural frequency can be actively changed in linear relation to the tuning voltage thereof.

Prior Art

Oscillators oscillating at a defined frequency are employed in all electronic devices to provide a time reference. When the oscillators are run at a defined frequency, the respective time elapse can be calculated by measuring the oscillator's oscillation number in a defined time interval. The frequency setting is necessary in this type of oscillators to bring a reference frequency, which may drift under external influences such as temperature, pressure, stresses occurring on the chips, or due to material fatigue, to a target frequency, or to fulfill the operation requirements under different frequencies.

Basically three types of oscillators are used according to the prior art. The first thereof is a full electronic type oscillator composed of electronic components such as a resistor, capacitor, and inductor. It is further known as a CMOS oscillator or a silicon clock. In this type of oscillators, resistor/capacitor (RC) or inductor/capacitor (LC) pairs are used such that signals are generated having frequencies which vary depending on the values of the components. The oscillating frequency of these oscillators can be changed by using a component with a variable value (e.g. a varactor or a variable resistor) therein. In this type of oscillators, however, heating problems are encountered due to high energy consumption, and no fine frequency adjustments can be made (particularly due to low quality factors). Besides, the adjustable oscillating frequency range of these oscillators is low.

A second type of oscillators according to the prior art are those oscillators having a quartz or a similar piezoelectric (electricity resulting from pressure) crystal structure. In this type of oscillators, a voltage is applied to a crystal piece so that the crystal piece is set into vibration at a certain frequency. Then, this vibration is converted into electrical signals such that electrical signals of a certain frequency are generated. A quartz crystal cut at certain directions is brought completely insensitive to temperature changes. Particularly this heat insensitivity and frequency stability, together with high quality factors render quartz more useful as compared to other crystal oscillators. In this type of oscillators, varactors or control units, e.g. a phase locked loop (PLL) can be used to change the oscillating frequency of the oscillator. Although this type of oscillators can be operated in a wide frequency range, the noise generated by said control units can give place to undesired influences in a circuit making use of the oscillator. At the same time, quartz and other piezoelectric crystals cannot be subjected to monolithic (by which all shaping steps are based on photolithography and the entire substrate is processed continuously in a parallel manner) chip integration due to the production type.

Another type of oscillator which is also disclosed in the patent documents US7591201B1 and US2007296527A1 according to the prior art is an oscillator based on a micro-electro-mechanical system (MEMS). In MEMS-based oscillators, a resonator which is in the form of a miniature mass produced particularly from a silicon (Si) material is set in vibration by an actuator element, and depending on this vibration, a signal with a certain frequency is read at a reading point. In this type of oscillators, a phase locked loop member can be used for controlling the frequency of the signal read at the reading point. Although that these oscillators have a lower frequency stability performance than those based on quartz, they are advantageous in terms of small-sized applications and system-integration. However, as is the case with those oscillators based on a crystal structure, the phase locked loop used for frequency adjustment in these oscillators is also a source of noise.

Brief Description of Invention

The present invention provides an oscillator having an adjustable oscillating frequency, as well as a method for producing this oscillator. Said oscillator comprises at least one micro-electro-mechanical system actuator which is capable to exert a tensile force to a member to which it is coupled by moving on a direction depending on the magnitude of a voltage applied; at least one nanomechanical resonator coupled from one of its ends to said actuator, and having an vibration frequency which changes by becoming deformed under the force exerted by the actuator; at least one feedback means measuring the stress value of the resonator and transmitting this value to the actuator; at least one actuator electrode, disposed at one side of the nanomechanical resonator leaving a space between itself and the resonator, and setting the resonator in vibration by the electrical field it applies to the resonator; and at least one reading electrode disposed at the other side of the resonator, such that the resonator is left between itself and the actuator electrode and a space is left between itself and the resonator, and generating a signal output at a certain frequency according to the vibrations of the resonator.

A method according to the present invention, in turn, comprises the steps of producing a resonator such that one of the ends thereof is coupled to an actuator and the other end thereof to a feedback means, and integrating the actuator electrode and the reading electrode into the structure of the resonator, actuator, and feedback means in a monolithic manner.

In the oscillator developed according to the present invention, the oscillating frequency of the oscillator can be adjusted by changing the stress applied to the actuator member. Additionally, since the entire components of the oscillator are produced in a micro-electro-mechanical system structure, the oscillator may be subjected to a rapid mass production in the form of a single circuit member.

Object of Invention

The object of the present invention is to develop a nanomechanical resonator based-oscillator having an adjustable oscillating frequency, as well as a method for producing this oscillator.

Another object of the present invention is to develop an oscillator operating under high frequencies so as to reach the microwave band, as well as a method for producing this oscillator.

A further object of the present invention is to develop an oscillator having a reversibly-adjustable oscillating frequency, as well as a method for producing this oscillator.

Another object of the present invention is to develop an oscillator having a wide range of adjustable oscillating frequencies, as well as a method for producing this oscillator.

A further object of the present invention is to develop an oscillator having an oscillating frequency linearly changing with the tuning voltage, as well as a method for producing this oscillator.

Another object of the present invention is to develop an oscillator having a low energy consumption, as well as a method for producing this oscillator.

A further object of the present invention is to develop an oscillator having an oscillating frequency which is (actively) adjustable without requiring any additional electronic control member, as well as a method for producing this oscillator.

Another object of the present invention is to develop a simply-produced oscillator by integrating a nanomechanical (nanowire, nanotube, nanoplate, graphene and similar nano-sized mechanical) resonator and actuator into sensor and converter systems in a monolithic fashion.

A further object of the present invention is to develop a method for producing an oscillator composed of a MEMS-based actuator, sensor, transducer system and a nanomechanical resonator in an entire on-chip solution and in full compatibility with other auxiliary electronic systems and micro-electro-mechanical systems.

Description of Figures

Illustrative embodiments of an adjustable oscillator and of a method for producing the same according to the present invention are illustrated in the accompanying figures briefly described hereunder.

Figure 1 illustrates a block diagram of the adjustable oscillator.

Figure 2 illustrates a detail "B" given in Figure 1.

Figure 3 illustrates an equivalent circuit of the adjustable oscillator.

Figure 4 illustrates a block diagram of a resonator production method in the oscillator production method.

Figure 5 illustrates a block diagram of an alternative resonator production method in the oscillator production method.

The components in said figures are individually designated as following.

Oscillator	(O)
Nanomechanical resonator	(T)
Actuator	(A)
Feedback means	(S)
Coupling element	(K)
Actuator electrode	(E1)
Reading electrode	(E2)
Resistor	(R)
Inductor	(L)
Capacitor	(C, C_0, C_F, C_P)
Power supply	(V_{AC}, V_{DC})
Output current	(i_t)
Silicon layer	(1)
Mask	(2)
Conformal layer	(3)
Catalyst	(4)
Mask application	(i)
Anisotropic etching	(ii)
Isotropic etching	(iii)
Conformal layer coating	(iv)
Physical etching	(v)
Multistage etching	(vi)
Mask and conformal layer removal	(vii)
Catalyst spreading and mask application	(a)
Resonator synthesizing	(b)

Multistage etching	(c)
Mask and catalyst removal	(d)

<u>Description of Invention</u>

Oscillators oscillating at a certain frequency are employed in all electronic devices as a time reference. These oscillators are also used as a filter element in various circuits operating at radio frequency (RF). The facts that a reference frequency may drift in time under external influences such as heat, pressure, stress, etc., or internal influences such as material fatigue, or the need for an oscillator which is capable to operate at the site at different programmable frequencies make frequency adjustment necessary. For this reason, tunable oscillators are used. However, the oscillators according to the prior are problematic in that the oscillator frequency thereof cannot be tuned or adjusted as desired, the adjustable frequency range is narrow, and in that any additional electronic components used for frequency adjustment (passive tuning) generate noise in the respective circuit. For this reasons, an oscillator which is based on a nanomechanical resonator is developed according to the present invention for avoiding these problems. The resonator may have a nanowire, nanotube, nanoplate, graphene or a similar form and is monolithically designed with the remainder of the oscillator and can operate at the microwave band by virtue of its low mass. Additionally, any frequency adjustment made has to be carried out separately from the external electronics, as well as in an active and reversible manner.

As illustrated in the block diagrams in figures 1 and 2, an oscillator (O) developed according to the present invention comprises at least one micro-electro-mechanical system actuator element (A) which is capable to exert a tensile force to a member to which it is coupled by moving on a direction depending on the magnitude of a voltage applied; at least one nanomechanical resonator (T) of a nanometric size (e.g. a nanowire, nanotube, nanoplate, graphene, etc.) coupled to said actuator, and having a vibration frequency which changes by becoming deformed under the tensile force exerted by the actuator element (A); at least one feedback means (S) measuring the stress value of the resonator (T) and transmitting this value to the actuator element (A); at least one actuator electrode (E1), disposed at one side of the resonator (T) leaving a space between itself and the resonator (T), and setting the resonator (T) in vibration by the electrical field it applies to the resonator (T); and at least one reading electrode (E2) disposed at the other side of the resonator, such that the resonator (T) is left between itself and the actuator electrode (E1) and a space is left between itself and the resonator (T), and generating a signal output at a certain frequency according to the vibrations of the resonator (T). In the oscillator (O) developed according to the present invention, the force exerted by the actuator element (A) to the resonator (T) varies depending on the voltage applied to the actuator element (A). Thus, the vibration frequency of the resonator (T) changes with varying the tensile force it experiences, and the signal frequency read at the reading electrode (E2) changes accordingly. Thus, an oscillator (O) having an easily-controlled oscillating frequency is developed according to the present invention.

Figure 3 illustrates an equivalent circuit of a setup according to the present invention which is composed of a resonator (T) with a tunable frequency, an actuator electrode (E1), and a reading electrode (E2). According to this equivalent circuit, the resonator (T) is polarized with a direct voltage (DC) power supply (V_{DC}), and the actuator electrode (E1) is driven by an alternating voltage (AC) power supply (V_{AC}). In this embodiment, when the frequency of the alternating voltage (electrical field) applied to the resonator (T) is equal to the natural frequency of the resonator (T), the resonator (T) shows a resonance behavior. In this case, the value of an output current (i_t) read by the reading electrode (E2) varies depending on the change of the distance between the resonator (T) and the reading electrode (E2). Here, the parasitic capacitance (C_p) of both electrodes (E1 and E2) made with the ground are shown in the circuit diagram as well. Additionally, the capacitor designated as C_0 indicates the static capacitance between the nanomechanical resonator (T) and each electrode (E1 and E2), whereas the capacitor indicated as C_F indicates the static capacitance between two electrodes (E1 and E2).

The current (i_t) which corresponds to the output signal of the circuit is composed of two components. The first of these components is a parasitic current which generates depending on the static capacitance (C_F) between the two electrodes (E1 and E2), on the static capacitance (C_0) between the nanomechanical resonator (T) and each electrode (E1 and E2 respectively), and on the alternating voltage (V_{AC}). The second component, in turn, is a movement-dependent current which varies with the movement of the nanomechanical resonator (T), and is actually to be used in following the resonator frequency. Using this equivalent circuit, the stages of these components in relation to each other, and therefore the success of a measurement are tested during the design phase.

R, L, and C values which make it possible to model the nanomechanical resonator (T) as an electrical component are determined by electromechanical analogy. When mechanical stress is induced on the nanomechanical resonator (T) by means of the actuator element (A), the R, L, and C values change and the values of these variables are updated in circuit simulation. The C_0, C_F, and C_P values, in turn, are calculated using the finite element method and entered to the circuit diagram. The R, L, and C values between both electrodes (E1 and E2) and the resonator (T) node are equivalent. And if the geometries of both electrodes (E1, E2) are equivalent, the two C_0 values in the circuit diagram are equivalent for these two electrodes (E1, E2) as well.

In a preferred embodiment according to the present invention, said feedback means (S) is in the form of a micro-electro-mechanical system displacement sensor, detecting the displacement of the resonator (T) of which the other end is coupled thereto (S). Said sensor measures the amount of force exerted by the actuator element (A) to the resonator (T). Thus, the stress data which depends on the amount of this displacement is signalized to the actuator element (A), such that the force exerted to the resonator (T) is accurately adjusted.

In an alternative embodiment according to the present invention, said feedback (S) means is in the form of a sensor which measures the oscillating frequency of the resonator (T) and calculates the tensile force on the resonator (T) according to the measured frequency data. This sensor may either be coupled to the reading electrode (E2) for measuring the output frequency from the reading electrode (E2), or may directly measure the oscillating frequency of the resonator (R). In this embodiment, the force exerted to the resonator (T) can be adjusted accurately by feeding the tensile force value generated based on the oscillating frequency data of the resonator (T) back to the actuator element (A).

In a preferred embodiment according to the present invention, the oscillator (O) comprises at least one coupling element (K) disposed between the actuator element (A) and the nanomechanical resonator (T), coupling the actuator element (A) and resonator (T) to each other, and preferably made of a material having an adjustable rigidity. By virtue of tuning the rigidity of said coupling element (K), a linear correlation will be obtained between the frequency drift of the output signal of the oscillator (O) and the voltage applied to the actuator element (A). In other words, by virtue of the coupling element (K) placed between the actuator element (A) and the resonator (T), adjustable frequency variations occur in direct proportion to the tuning voltage applied to the actuator element (A) (the frequency of the signal read at the reading electrode (E2) varies linearly with respect to the voltage applied to the actuator element (A)).

In a preferred embodiment according to the present invention, the resonator (T), the actuator element (A), and the feedback means (S) which is in the form of a displacement sensor are produced monolithically for the integration of micro- and nano-scaled components in the same production process. Thus, the system according to the present invention can be subjected to mass production.

In a preferred embodiment according to the present invention, the resonator (T), the actuator element (A), and the feedback means (S) are produced into a single-piece structure, preferably from a single silicon crystal layer, if a silicon nanometric resonator (T) is used. According to this embodiment, the requirement to bind the components to each other is eliminated by virtue of the single-piece structure thereof. Accordingly, since no foreign substance such as an adhesive is provided between the resonator (T) and the actuator element (A), as well as between the resonator (T) and the sensor (S), these components may be operated more compatibly among themselves and any breaks which may occur at the interfaces are prevented.

In another preferred embodiment according to the present invention, the oscillator (O) comprises at least one pretension sensor controlling the pretensions which occur at the resonator (T) following the production of the oscillator (O). According to this embodiment, the force exerted by the actuator element (A) to the resonator (T) (i.e. the oscillating frequency of the resonator (T)) may be tuned by using the pretension values measured by the pretension sensor.

In a method for producing an oscillator (O) according to the present invention, the resonator (T) is so produced that it is coupled to the actuator element (A) at one of its ends, and to the feedback means (S) from its other end. Then, the actuator electrode (E1) and the reading electrode (E2) are integrated into the structure of the resonator (T), actuator element (A), and the feedback means (S) in a monolithic manner. Thus, the entire components of the oscillator (O) are produced in a monolithic fashion.

As illustrated in Figure 4, a preferred embodiment of the production method of the resonator (T) according to the present invention comprises the steps of applying a mask (2) with a defined pattern to provide insulation against ion etching on a silicon layer (1), so that a resonator (T), an actuator element (A) and a feedback means (S) are formed (i); anisotropically etching the parts of the silicon layer (1) which are free of the mask (2) up to a defined depth by means of a reactive ion etching method (ii); isotropically etching those parts which were subjected to anisotropic etching (iii); coating the outer surface of the silicon layer (1) with a conformal layer (3) (iv); subjecting the conformal layer (3) on the horizontal surfaces to physical etching (v); forming the actuator element (A) and the feedback means (S) by multistage etching such as a Bosch process (vi); and removing the mask (2) and the conformal layer (3) (vii). According to this embodiment, the resonator (T) is formed from the silicon layer (1). Additionally, by virtue of the manner by which the mask (2) is applied to the silicon layer (1), the resonator (T) can be produced such that one end thereof is coupled to the actuator element (A), and the other end thereof to the feedback means (S).

In an alternative embodiment according to the present invention, the resonator (T) is produced from a material (e.g. nanowires, nanotubes, and nanoplates which are made of graphene, carbon nanotube, etc.) other than silicon, and is integrated such that one end thereof (T) is coupled to the actuator element (A) and the other end thereof to the feedback means (S), by the production method as illustrated in Figure 5. Said method comprises the steps of (a) applying a mask (2) and at least one catalyst (4) with a defined pattern to provide insulation against ion etching on a silicon layer (1), so that an actuator element (A) and a feedback means (S) are formed; (b) synthesizing the resonator (T) via said catalyst (4); (c) releasing the resonator (T) by applying a multistage etching e.g. a Bosch process and forming the actuator element (A) and the feedback means (S); and (d) removing the mask (2) and the catalyst (4). According to this embodiment, even if the resonator (T) is made of a material other than silicon, it can be monolithically integrated to the feedback means (S) and the actuator element (A) made of silicon.

In an alternative embodiment according to the present invention, a material layer (e.g. a metallic layer obtained using electrochemical coating) different than a silicon layer (1) can be used to form the actuator element (A) and the feedback means (S), as illustrated in Figure 5.

In the oscillator (O) developed according to the present invention, the frequency of the signal read at the output electrode (E2) varies linearly according to the voltage applied to the actuator element (A). Thus, the oscillating frequency of the oscillator (O) can be simply controlled. Additionally, since a MEMS-based actuator element (A), a MEMS-based displacement sensor (S), and a nanomechanical resonator (T) are used in this oscillator (O), it can oscillate at high frequencies reaching the microwave band in a wide frequency range and have a low energy consumption. Additionally, since no control units such as a phase locked loop or varactor is used to change the oscillating frequency of the oscillator (O), noise generation is also prevented in the circuit in which the oscillator (O) is used. Furthermore, the production method according to the present invention provides a rapid and safe oscillator production.

CLAIMS

1. An oscillator (O) with an adjustable oscillating frequency, characterized by comprising
   - at least one micro-electro-mechanical system actuator element (A) which is capable to exert a tensile force to a member to which it is coupled by moving on a direction depending on the magnitude of a voltage applied;
   - at least one nanomechanical resonator (T), having one end coupled to said actuator element (A), and having a vibration frequency which changes by becoming deformed under the force exerted by the actuator (A);
   - at least one feedback means (S) measuring the stress value of the resonator (T) and transmitting this value to the actuator element (A);
   - at least one actuator electrode (E1), disposed at one side of the nanomechanical resonator (T) leaving a space between itself (E1) and the resonator (T), and setting the resonator (T) in vibration by the electrical field it applies to the resonator (T); and
   - at least one reading electrode (E2) disposed at the other side of the resonator (T), such that the resonator (T) is left between itself (E2) and the actuator electrode (E1) and a space is left between itself (E2) and the resonator (T), and generating a signal output at a certain frequency as a function of the vibrations of the resonator (T).

2. The oscillator (O) according to claim 1, characterized in that said feedback means (S) is in the form of a micro-electro-mechanical system displacement sensor, detecting the displacement of the resonator (T) of which the other end is coupled thereto (S).

3. The oscillator (O) according to claim 1, characterized in that the actuator element (A), the feedback means (S), and the resonator (T) are produced into a monolithic structure.

4. The oscillator (O) according to claim 1, characterized in that said feedback means (S) is in the form of a sensor which measures the oscillating frequency of the

resonator (T) and calculates the tensile force on the resonator (T) based on the measured frequency data.

5. The oscillator (O) according to claim 1, characterized by comprising at least one coupling element (K) disposed between the actuator element (A) and the nanomechanical resonator (T) and coupling the actuator element (A) and the resonator (T) to each other.

6. The oscillator (O) according to claim 5, characterized in that said coupling element (K) is made of a material having an adjustable rigidity.

7. The oscillator (O) according to claim 1, characterized by comprising at least one pretension sensor controlling the pretensions which occur at the resonator (T) following the production of the oscillator (O).

8. A method for producing an oscillator (O) having an adjustable oscillating frequency, characterized by comprising the steps of

- producing at least one nanomechanical resonator (T) so that one end of the resonator (T) is coupled to at least one micro-electro-mechanical system actuator element (A), which is capable to exert a tensile force on a member to which it is coupled by moving in a direction depending on the magnitude of a voltage applied, and that the other end of the resonator (T) is coupled to at least one feedback means (S), which measures the stress value of the resonator (T) and transmits this value to the actuator element (A);
- integrating at least one actuator electrode (E1) which sets the resonator (T) in vibration by the electrical field it applies to the resonator (T), and at least one reading electrode (E2) generating a signal output at a certain frequency based on the vibrations of the resonator (T) into the structure of the resonator (T), the actuator element (A), and the feedback means (S) in a monolithic manner so that the resonator (T) is left between the actuator electrode (E1) and the reading electrode (E2).

9. The method for producing an oscillator (O) according to claim 8, characterized in that the production of the resonator (T) comprises the steps of

- applying a mask (2) with a defined pattern to provide insulation against ion etching on a silicon layer (1), so that a resonator (T), an actuator (A) and a feedback means (S) are formed (i);
- anisotropically etching the parts of the silicon layer (1) which are free of the mask (2) up to a defined depth by means of a reactive ion etching method (ii);
- isotropically etching those parts which were subjected to anisotropic etching (iii);
- coating the outer surface of the silicon layer (1) with a conformal layer (3) (iv);
- subjecting the conformal layer (3) on the horizontal surfaces to physical etching (v);
- forming the actuator element (A) and the feedback means (S) by a multistage etching application (vi); and
- removing the mask (2) and the conformal layer (3) (vii).

10. The method for producing an oscillator (O) according to claim 8, characterized in that the production of the resonator (T) comprises the steps of

- applying a mask (2) and at least one catalyst (4) with a defined pattern to provide insulation against ion etching on a silicon layer (1), so that an actuator element (A) and a feedback means (S) are formed (a);
- synthesizing the resonator (T) made of a material other than silicon via the catalyst (4) applied on the silicon layer (1) (b);
- releasing the resonator (T) by applying a multistage etching process and forming the actuator element (A) and the feedback means (S) (c); and
- removing the mask (2) and the catalyst (4) (d).

11. The method for producing an oscillator (O) according to claim 10, characterized in that the actuator element (A) and the feedback means (S) are manufactured from a material layer other than a silicon layer (1).

12. The method for producing an oscillator (O) according to claim 9 or 10, characterized in that the multistage etching process is a Bosch process.

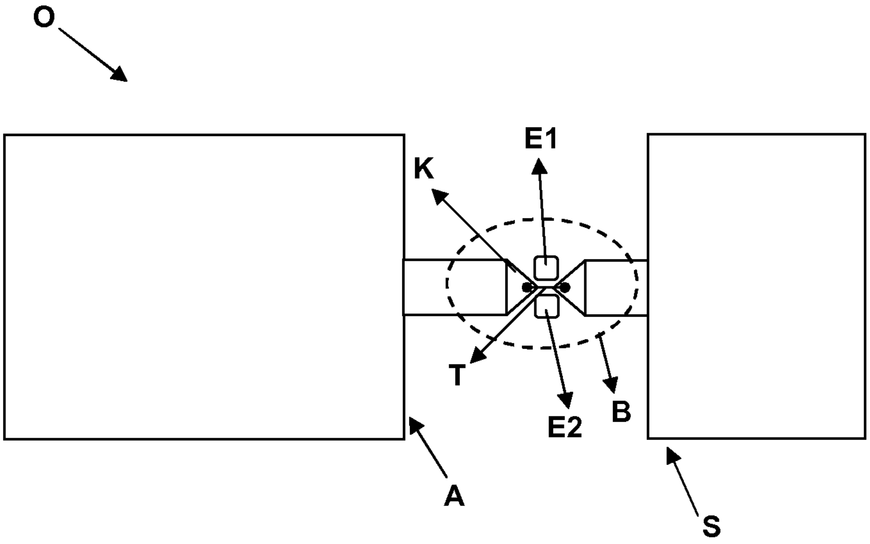

Figure – 1

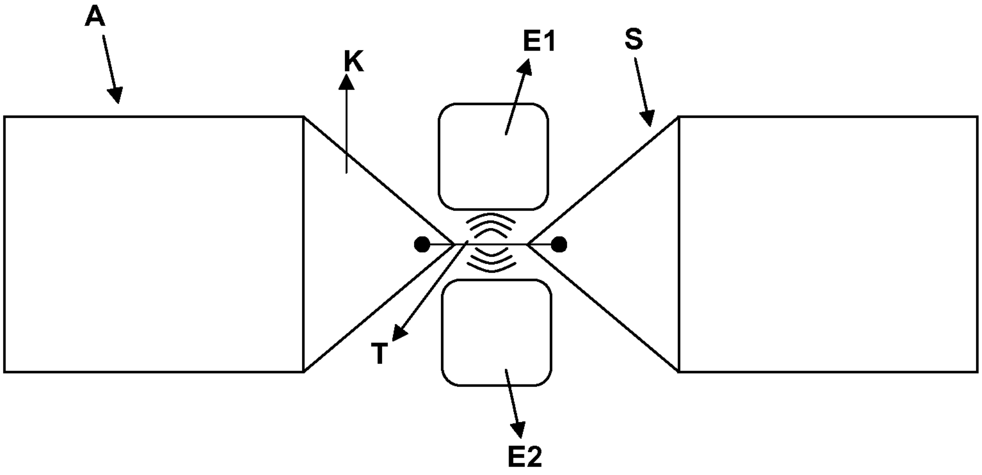

Figure – 2

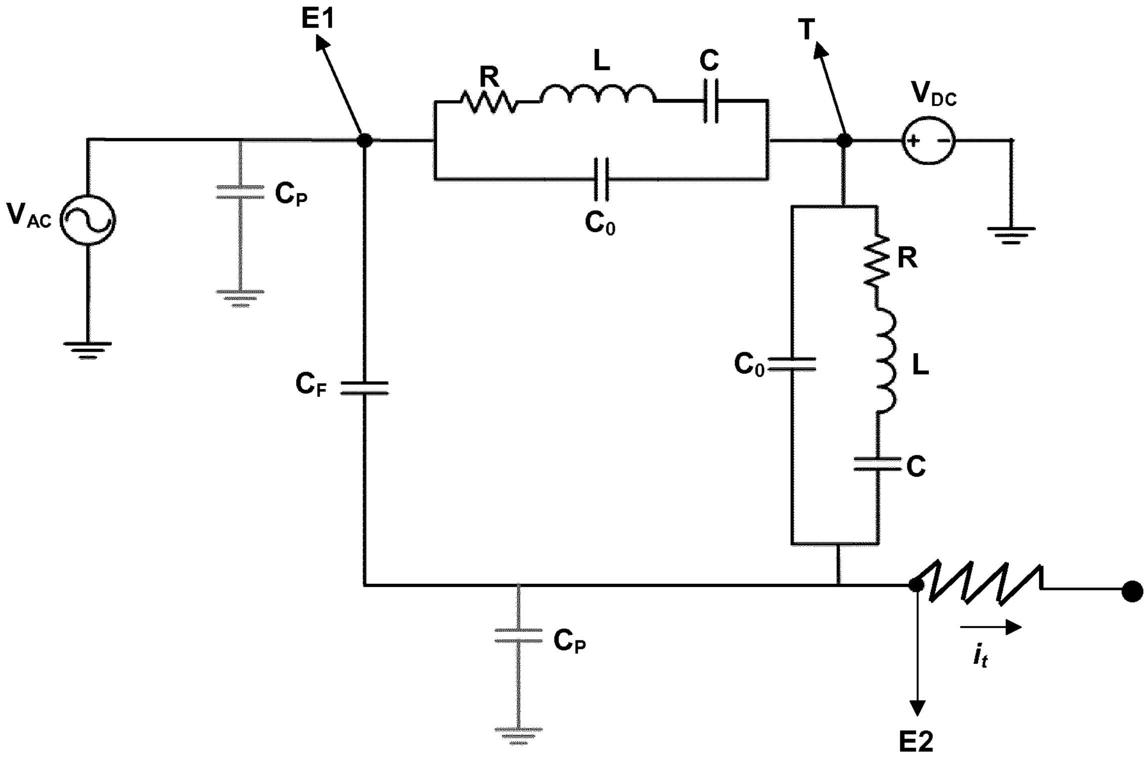

Figure – 3

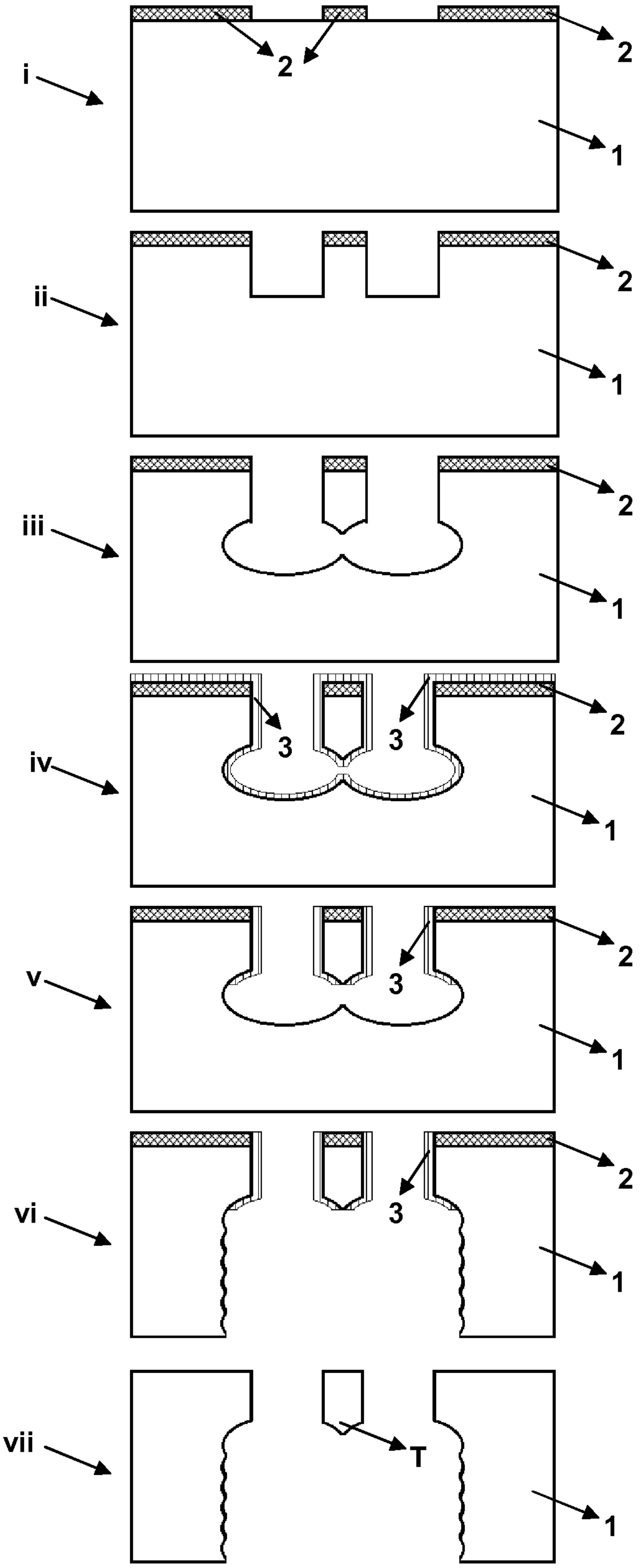

Figure – 4

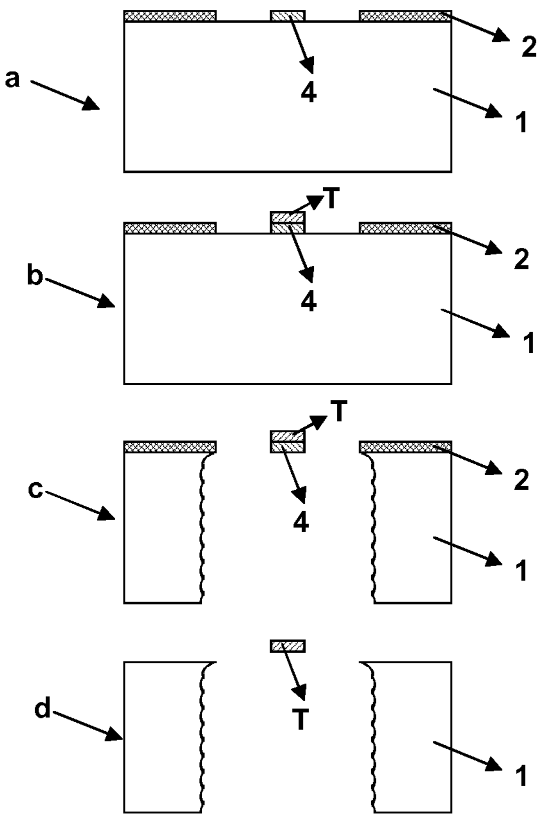

Figure – 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/064220

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03H3/007 H03H9/02 H03H9/24
ADD.

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)
H03H H03B B81C

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.
X	US 2007/214890 A1 (MUKHERJEE RANJAN [US]) 20 September 2007 (2007-09-20) paragraphs [0005], [0009], [0023], [0026], [0029], [0030]; figures 1,5,6 -----	1-9,12
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/064220

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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