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(54) **Title:** BAW RESONATOR WITH REDUCED SPURIOUS MODES AND INCREASED QUALITY FACTOR

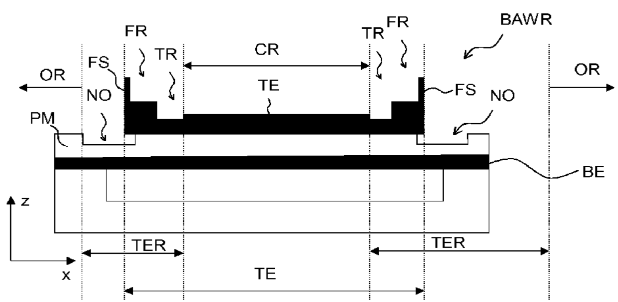

Fig. 1

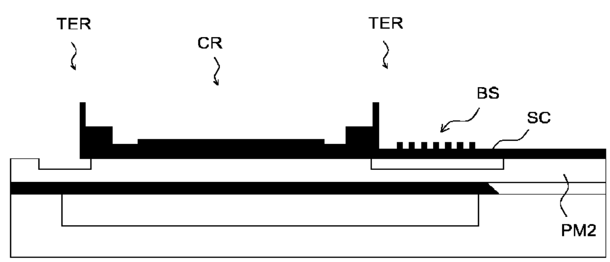

Fig. 4

(57) **Abstract:** An electrically and acoustically improved resonator is provided. The resonator (BAWR) has a center region (CR) and a termination region (TER) surrounding the center region. A trench (TR) in a top electrode (TE), a frame (FR) on the top electrode, a flap structure (FS) connected to the frame and a notch (NO) in a piezoelectric layer reduce spurious modes and increase the quality factor of the resonator. A lateral Bragg reflector may be realized with a Bragg structure (BS) on a signal conductor (SC) in the top electrode layer spanning the notch.

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Description

BAW resonator with reduced spurious modes and increased quality factor

The present invention refers to BAW resonators, e.g. for RF filters, having improved acoustic and electric properties.

BAW resonators (BAW = bulk acoustic wave) can be used to build bandpass or band rejection filters for RF applications, e.g. wireless communication devices. Such devices can use filters comprising such resonators. Usually, wireless communication devices have an energy source with limited energy resources and power saving circuits are preferred.

BAW resonators have a sandwich construction with a piezoelectric material between a bottom electrode and a top electrode. Due to the piezoelectric effect such resonators convert between RF signals and acoustic waves if an RF signal is applied to the resonators' electrodes.

An ideal BAW resonator has a certain extension along the thickness direction characterized by the wave factor of the wanted acoustic main mode. The ideal resonator, however, is not limited in lateral directions. Thus, oscillations in one dimension are obtained.

However, real resonators have limited lateral dimensions and the resonator is mechanically connected to its environment. Due to finite lateral dimensions and necessary means for mechanical and electrical connections, unwanted spurious modes can occur and the quality factor is reduced. In particular, acoustic energy can dissipate in the resonator's environment.

BAW resonators are known from US 9,571,063 B2 and from US 9,219,464 B2.

What is wanted is a BAW resonator with reduced spurious modes and an increased quality factor. A BAW resonator according to independent claim 1 is provided. Dependent claims provide preferred embodiments.

The BAW resonator having reduced spurious modes and an increased quality factor comprises a bottom electrode, a top electrode and a piezoelectric material. The bottom electrode is arranged in a bottom electrode layer, the top electrode is arranged in a top electrode layer, and the piezoelectric material is arranged in a piezoelectric layer. The piezoelectric layer is arranged between the bottom electrode layer and the top electrode layer. The BAW resonator further has a center region provided for converting between RF signals and acoustic waves and an outer region surrounding the center region. Further, the BAW resonator has a termination region between the center region and the outer region. The termination region is provided for acoustically decoupling the outer region from the center region. Further, the BAW resonator has a trench in the top electrode layer. The trench surrounds the center region. Additionally, the resonator has a frame on the top electrode. The frame surrounds the trench. Further, the BAW resonator has a flap structure mechanically connected to the frame and provided for counterbalancing oscillations of the center region. Additionally, the BAW resonator has a notch in the piezoelectric material. The notch surrounds the center region.

Thus, a BAW resonator is provided where a termination region acting as a termination of the center region acoustically separates the acoustically active center region from the resonator's environment to reduce energy dissipation in the resonator's environment. The trench in the top electrode, the frame on the top electrode, the flap structure and the notch are acoustically effective structures of the termination region that have an essential impact on the acoustical decoupling.

A result of the acoustical decoupling is that acoustic energy cannot reach the resonator's environment. The above mentioned structures help reflecting acoustic energy back into the active center region. Thus, drain of acoustic energy is reduced and the quality factor is increased.

Further, the trench, the frame, the flap structure and the notch act together to shape the oscillation mode in order to avoid spurious modes.

As a consequence, a BAW resonator with improved electric and acoustic properties is obtained.

Two or more such BAW resonators can be electrically connected to build a bandpass filter or band rejection filter, e.g. in a ladder type configuration.

It is possible that the BAW resonator further comprises a signal conductor in the top electrode layer between the center region and the outer region.

The signal conductor electrically connects the top electrode to an external circuit environment, e.g. to other resonators or to an input port or to an output port of an RF filter.

Similarly, the bottom electrode may be electrically connected to other resonators, to an input port, to an output port or to the ground terminal of an RF filter.

Creating a BAW resonator involves a plurality of manufacturing steps for creating the layer stack. Means for confining acoustic energy to the center region or to avoid or suppress spurious modes are preferably arranged at the top side of the resonator as the resonator itself may be arranged on or above a carrier substrate and creating acoustically active structures below the resonator stack would render manufacturing steps more difficult.

However, unavoidable electrical connections, e.g. of the top electrode, establish paths via which acoustic energy can dissipate. Thus, preferably the signal conductor electrically connects the top electrode only in a limited area.

The signal conductor can comprise material of the top electrode layer. In particular, the signal conductor can consist of material of the top electrode layer that remains after a structuring process in which material of the top electrode layer is removed in the surroundings of the termination region.

It is possible that the BAW resonator comprises an acoustic mirror arranged in the termination region. The acoustic mirror is provided for suppressing lateral leakage.

The relationship between the different layers is such that the different layers are stacked one above the other in a direction z parallel to the wave vector of the acoustic main mode. In contrast, the terms center region, outer region and termination region determine lateral areas seen in a top view when the viewing direction is parallel to the wave vector.

Thus, the termination region surrounds the center region in a lateral direction, and the outer region surrounds the termination region and the center region in a lateral direction.

It is possible that the acoustic mirror comprises the notch and a Bragg structure on the signal conductor.

The notch is an effective means for suppressing leakage of acoustic energy in a vicinity of the top side of the piezoelectric layer. To electrically connect the top electrode the signal conductor bridges the notch and generally establishes a path for acoustic energy towards the resonator's environment. To prevent acoustic energy from dissipating in the resonator's environment the Bragg structure can comprise the creating structure of stripes acting as a Bragg mirror for acoustic waves. The Bragg structure has a periodic structure along the lateral direction x in which sections of high acoustic impedance and low acoustic impedance are iteratively arranged. To that end, stripes of a material, e.g. of the material of the top electrode, are arranged on the signal conductor.

It is possible that material of the signal conductor is thinner at an acoustic null to reduce flexural mode excitation. An acoustic null is a place where acoustic oscillations have a minimum amplitude, i.e. a node. By making the signal conductor thinner in this position compared to the environment of the acoustic nulls, flexural mode excitation is reduced and lateral leakage is further suppressed.

It is possible that the piezoelectric material comprises AlN (aluminum nitride) or AlScN (aluminum scandium nitride) or scandium doped aluminum nitride. However, the use of ZnO (zinc oxide) and PZT (LED circonate titanate) is also possible.

The material of the bottom electrode or of the top electrode can comprise materials selected from tungsten, an aluminum copper alloy, titanium, titanium nitride, molybdenum, gold, silver, copper, alloy comprising silver and copper, iridium, ruthenium and platinum.

It is possible that sidewalls of the notch are an interface between areas of different acoustic impedance.

The acoustic impedance is characteristic of a material and depends on the velocity of sound and the density of the material. The acoustic impedance Z increases with increasing density ρ and with increasing sound velocity v. The sound velocity v depends on parameters like stiffness parameters c of the materials and the density ρ: e.g. $v = sqrt(c/ \rho)$ and $Z = sqrt(c*\rho))$.

An interface between areas of different acoustic impedance reflects acoustic waves at least partially.

It is possible that the notch is empty, filled with a gas or filled with a dielectric material.

It is possible that the piezoelectric layer comprises an etch stop layer with respect to the piezoelectric material.

Thus, the etch stop layer comprises a material that differs in etching properties from the piezoelectric material otherwise contained in the piezoelectric layer.

The etch stop layer simplifies creating the notch. In this case, the depth of the notch equals the thickness of the piezoelectric material in the piezoelectric layer above the etch stop layer.

It is possible that the etch stop layer comprises wurtzite ((Zn,Fe)S) or a material with the structure of wurtzite or a similar structure. The structure of the etch stop layer can have a hexagonal lattice symmetry such as a 4H-SiC (silicon carbide). Then crystal growth of the piezoelectric above is promoted while a good etch selectivity is achieved.

By providing such an etch stop layer the depth of the notch can be adjusted with the high precision.

It is possible that the piezoelectric layer comprises a first piezoelectric material on the bottom electrode and a second, different piezoelectric material on the first piezoelectric material.

In particular, it is preferred that the first piezoelectric material and the second piezoelectric material can be selectively etched with respect to each other. Then, the surface of the first piezoelectric material can act as an etch stop surface to create the notch which is arranged in the second piezoelectric layer and which is established by locally fully removing material of the second piezoelectric material.

Correspondingly, it is possible that the depth of the notch equals the thickness of the second piezoelectric material.

It is possible that the flap structure is oriented in an angle with respect to the wave vector of a main mode of the resonator. The angle can be selected from 0°, 45°, 90°, 135°. In this case, when the angle is 45°, the flap structure points towards the top side. When the angle equals 135°, the flap structure points towards the bottom side. However, other angles are also possible. The angle can be, e.g., between 0° and 45° or between 45° and 90° or between 90° and 135° or between 135° and 180°.

It is possible that the flap structure has a sidewall. The sidewall can be arranged directly above a sidewall of the notch or within an area surrounded by the notch.

Thus, it is possible that the flap structure and the notch are aligned with respect to each other. However, it is possible that the flaps are arranged in an area surrounded by the notch.

It is possible that the BAW resonator further comprises a passivation layer. The passivation layer can cover segments of the top side of the top electrode, the bottom side of the top electrode, the surface of the frame, the surface of the flap structure, the surface of the trench and/or the surface of the signal conductor.

The passivation layer can comprise or consist of aluminum nitride or silicon nitride. Such a layer can also act as a trim layer.

It is possible that the BAW resonator is an FBAR-type resonator or an SMR-type resonator.

In an FBAR-type resonator (FBAR = film bulk acoustic resonator) a cavity below the bottom electrode is arranged to acoustically decouple the resonator in a vertical direction.

In an SMR-type resonator an acoustic mirror is arranged below the bottom electrode. The acoustic mirror comprises layers of high and low acoustic impedance working as a Bragg reflector to confine acoustic energy to the active area of the resonator and to suppress vertical leakage of acoustic energy.

It is to be noted that the trench in the top electrode is characterized by a recess in the top electrode. This means that the trench is located at an area where the thickness of the top electrode is smaller than the thickness of the top electrode in the center region.

In contrast, the frame is characterized by additional material. The thickness of the material above the piezoelectric layer is higher than the thickness of the top electrode in the center region.

Correspondingly, the notch is characterized as a recess in the piezoelectric layer.

It is to be noted that the notch can be empty or comprise a dielectric material such that the parasitic capacitance of the resonator, i.e. the static capacitance of the resonator outside the center region (e.g. in the top electrode connection) is reduced.

Bandpass filters established with at least one such resonator can have a reduced ripple in the pass band. The quality factor is increased and thus energy drain from a battery, e.g. of a mobile communication device, is reduced. The insertion loss of the corresponding RF filter is reduced. Central working principles and details of preferred embodiments are shown in the accompanying schematic figures.

In the figures:

Fig. 1 and Fig. 3 show cross-sections through a resonator.

Fig. 2 shows a top view onto a resonator stack.

Fig. 4 shows a cross-section through a resonator stack having a Bragg structure in the top electrode connection.

Fig. 5 shows the possibility of using another piezoelectric material.

Fig. 6 shows the use of an etch stop layer.

Fig. 7 shows the use of different piezoelectric materials.

Figs. 8 to 11 show different possible shapes of the flap structure.

Fig. 12 shows a notch filled with a dielectric material.

Fig. 13 shows the flap structure aligned with the sidewall of the notch.

Fig. 14 shows the application of a passivation layer.

Fig. 15 shows a vertically aligned flap structure.

Fig. 16 shows an SMR-type resonator.

Fig. 17 shows the efficiency of the Bragg structures on the signal conductor.

Figs. 1, 2 and 3 show different cross-sections (Figs. 1 and 3) and top views (Fig. 2) of a BAW resonator. The resonator has a bottom electrode BE and a top electrode TE. Between the two electrodes a piezoelectric material PM is arranged in the piezoelectric layer PL. The layer stack describes the construction of the resonator in the z-direction, i.e. parallel to the wave vector of the main acoustic mode. The layers extend along the xy plane orthogonal to the z-direction. The center region CR of the resonator is provided to be the active resonator region where conversion between RF signals and acoustic waves is essentially performed. The center region CR is surrounded by the termination region TER which shall acoustically decouple the center region CR from the outer region OR. Within the termination region a trench TR in the top electrode and a frame structure FR and a flap structure FS on the top electrode are provided. Further, a notch NO in the piezoelectric material below the top electrode is also provided. The trench TR, frame FR flap FS and notch NO act as acoustically effective means to suppress unwanted spurious modes and to confine acoustic energy within the resonator. In order to electrically connect the top electrode TE although the center region CR is surrounded by the notch NO the signal conductor SC bridges the notch. Correspondingly, Fig. 3 shows a cross-section through the layer stack at position BB while Fig. 1 shows a cross-section at position AA.

Fig. 4 shows the possibility of limiting lateral leakage further by establishing a creating structure in the form of a Bragg structure BS on the signal conductor SC.

Fig. 5 shows the possibility of using different piezoelectric materials between the two electrodes.

The dimensions (depth [extension along direction z], width [extension across direction x or y]) are adapted to the characteristic acoustic properties of the piezoelectric material.

Fig. 6 illustrates the use of an etch stop layer ESL within the piezoelectric layer to allow the notch to have a highly homogenous depth.

Fig. 7 shows the use of interlayers of different piezoelectric materials within the piezoelectric layer. Thus, on the bottom electrode a piezoelectric sublayer with the first piezoelectric material PM1 is arranged. On this sublayer a second sublayer comprising a second piezoelectric material PM2 is arranged. Concerning an etching agent, e.g.

hydrofluoric acid, the etch rates of the first piezoelectric material PM1 and the second piezoelectric material PM2 are different. Thus, the two piezoelectric materials are practically selectively etchable with respect to one another and an etch stop interface ESI is obtained, which allows a homogenous depth of the notch in the second piezoelectric material PM2.

The first piezoelectric material PM1 and the second piezoelectric material PM2 can be selected from aluminum nitride and scandium doped aluminum nitride, which have different etching rates with respect to hydrofluoric acid.

Fig. 8 shows an embodiment where the flap structure is arranged in a 90° orientation with respect to the wave vector of the acoustic main mode.

Fig. 9 illustrates an embodiment where the angle between the flap structure and the wave vector is 45°. The flap structure points towards the outer region of the resonator.

Fig. 10 illustrates the possibility of a 45° angle between the wave vector and the flap structure. However, the flap structure points towards the center region of the resonator.

Fig. 11 shows the possibility of an angle of 135° while the flap structure points towards the outer region.

Fig. 12 illustrates the possibility of filling the notch NO with the dielectric material DM. In this case, the notch NO can be created by establishing a recess that is filled with the dielectric material DM before the material of the top electrode is deposited. Thus, after polishing the top side of the piezoelectric material and the dielectric material, the top electrode and the signal conductor can be deposited and created on a smooth surface and in a high quality.

Fig. 13 shows the possibility of vertically aligning the flap structure FS, in particular a sidewall of the flap structure FS and a sidewall SW of the notch.

Fig. 14 illustrates the possibility of protecting the resonator by arranging a passivation layer PAS on the accessible surfaces and below the material of the top electrode.

Fig. 15 illustrates a preferred embodiment where the flap structure FL is aligned orthogonal to the wave vector and extends above the notch in the piezoelectric material.

While Figs. 1 to 15 exemplarily show the resonator structure above the cavity, Fig. 16 shows the use of an electroacoustic mirror EAM below the bottom electrode.

Fig. 17 illustrates the efficiency of a Bragg structure BS to acoustically decouple the center region CR from the resonator surroundings. In particular, Fig. 17 shows a simulated section of the resonator indicating oscillations OSC in the center region CR and in the section of the signal conductor SC pointing towards the center region CR and above the notch NO. Acoustic waves propagate in the corresponding segment of the signal conductor SC. However, the Bragg structures BS efficiently reflect the acoustic waves back to the center region CR and practically no oscillations take place at the signal conductor SC beyond the Bragg structure. Thus, the center region CR is well acoustically decoupled and the signal conductor SC gives no contribution to leakage.

The BAW resonator is not limited to the technical details explained above and shown in the figures. BAW resonators comprising further layers, reflecting structures and acoustically effective means for confining acoustic energy to the center region are also covered.

List of reference signs

BAWR	BAW resonator
BE	Bottom electrode
BEL	bottom electrode layer
BS	Bragg structure
CR	center region
DM	dielectric material
ESI	etch stop interface
ESL	etch stop layer
FR	frame
FS	flap structure
NO	notch
OR	outer region
OSC	oscillation
PAS	passivation layer
PL	piezoelectric layer
PM	piezoelectric material
PM1	first piezoelectric material
PM2	second piezoelectric material
SC	signal conductor
SW	sidewall
TE	top electrode
TEL	top electrode layer
TER	termination region
TR	trench
x, y	lateral directions
z	vertical direction

Claims

1. A BAW resonator (BAWR) with reduced spurious modes and increased quality factor, comprising
- a bottom electrode (BE) in a bottom electrode layer (BEL), a top electrode (TE) in a top electrode layer (TEL), and a piezoelectric material (PM) in a piezoelectric layer (PL) arranged between the bottom electrode layer (BEL) and the top electrode layer (TEL),
- a center region (CR) provided for converting between RF signals and acoustic waves, an outer region (OR) surrounding the center region (CR), and a termination region (TER) between the center region (CR) and the outer region (OR), the termination region (TER) being provided for acoustically decoupling the outer region (OR) from the center region (CR),
- a trench (TR) in the top electrode layer (TEL), the trench (TR) surrounding the center region (CR),
- a frame (FR) on the top electrode (TE), the frame (FR) surrounding the trench (TR),
- a flap structure (FS) mechanically connected to the frame (FR) and provided for counterbalancing oscillations of the center region (CR),
- a notch (NO) in the piezoelectric material (PM), the notch (NO) surrounding the center region (CR).

2. The BAW resonator of the previous claim, further comprising a signal conductor (SC) in the top electrode layer (TEL) between the center region (CR) and the outer region (OR).

3. The BAW resonator of one of the previous claims, comprising an acoustic mirror arranged in the termination

region (TER), the acoustic mirror being provided for suppressing lateral leakage.

4. The BAW resonator of the previous claim, where the acoustic mirror comprises the notch (NO) and a Bragg structure (BS) on the signal conductor (SC).

5. The BAW resonator of one of the previous claims, where the material of the signal conductor (SC) is thinner at an acoustic null to reduce flexural mode excitation.

6. The BAW resonator of one of the previous claims, where the piezoelectric material (PM) comprises AlN or AlScN.

7. The BAW resonator of one of the previous claims, where sidewalls of the notch (NO) are an interface between areas of different acoustic impedance Z.

8. The BAW resonator of one of the previous claims, where the notch (NO) is empty, filled with a gas or filled with a dielectric material (DM).

9. The BAW resonator of one of the previous claims, where the piezoelectric layer (PL) comprises an etch stop layer (ESL) with respect to the piezoelectric material (PM).

10. The BAW resonator of the previous claim, where the etch stop layer comprises wurtzite or a material with a hexagonal lattice or a silicon carbide.

11. The BAW resonator of one of the previous claims, where the piezoelectric layer (PL) comprises a first piezoelectric material (PM1) on the bottom electrode (BE) and a second,

different piezoelectric material (PM2) on the first piezoelectric material (PM1).

12. The BAW resonator of the previous claim, where the depth of the notch (NO) equals the thickness of the second piezoelectric material (PM2).

13. The BAW resonator of one of the previous claims, where the flap structure (FS) is oriented in an angle with respect to the wave vector of a main mode of the resonator, the angle being selected from 0°, 45°, 90°, 135°.

14. The BAW resonator of one of the previous claims, where the flap structure (FS) has a sidewall arranged
- directly above a sidewall of the notch (NO) or
- within an area surrounded by the notch (NO).

15. The BAW resonator of one of the previous claims, further comprising a passivation layer (PAS) covering segments of
- the top side of the top electrode (TE),
- the bottom side of the top electrode (TE),
- the surface of the frame (FR),
- the surface of the flap structure (FS),
- the surface of the trench (TR) and/or
- the surface of the signal conductor (SC).

16. The BAW resonator of one of the previous claims, the resonator being an FBAR-type resonator or an SMR-type resonator.

17. An RF-filter comprising one or more BAW resonators of one of the previous claims.

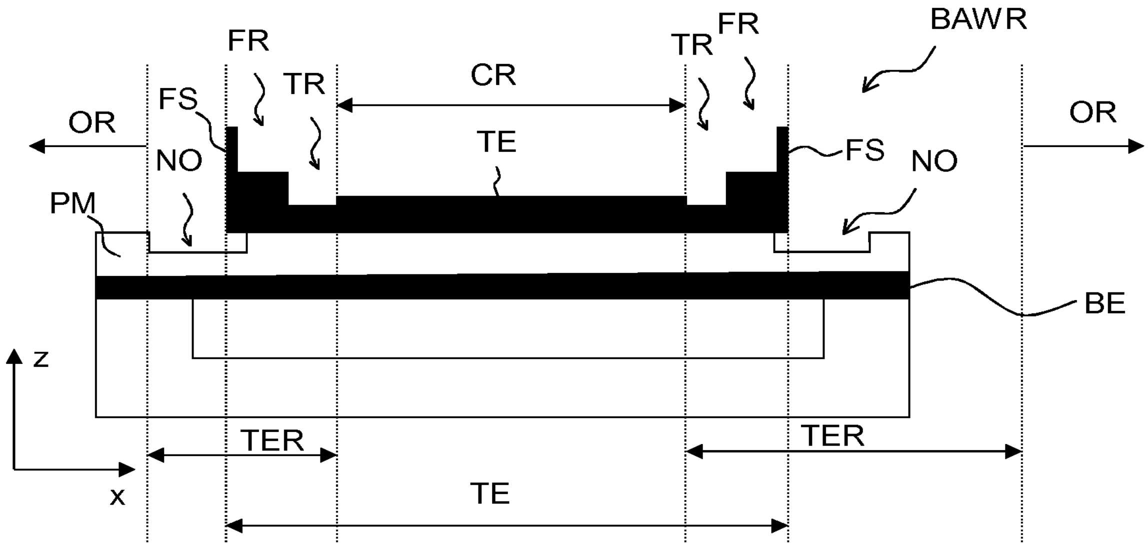

Fig. 1

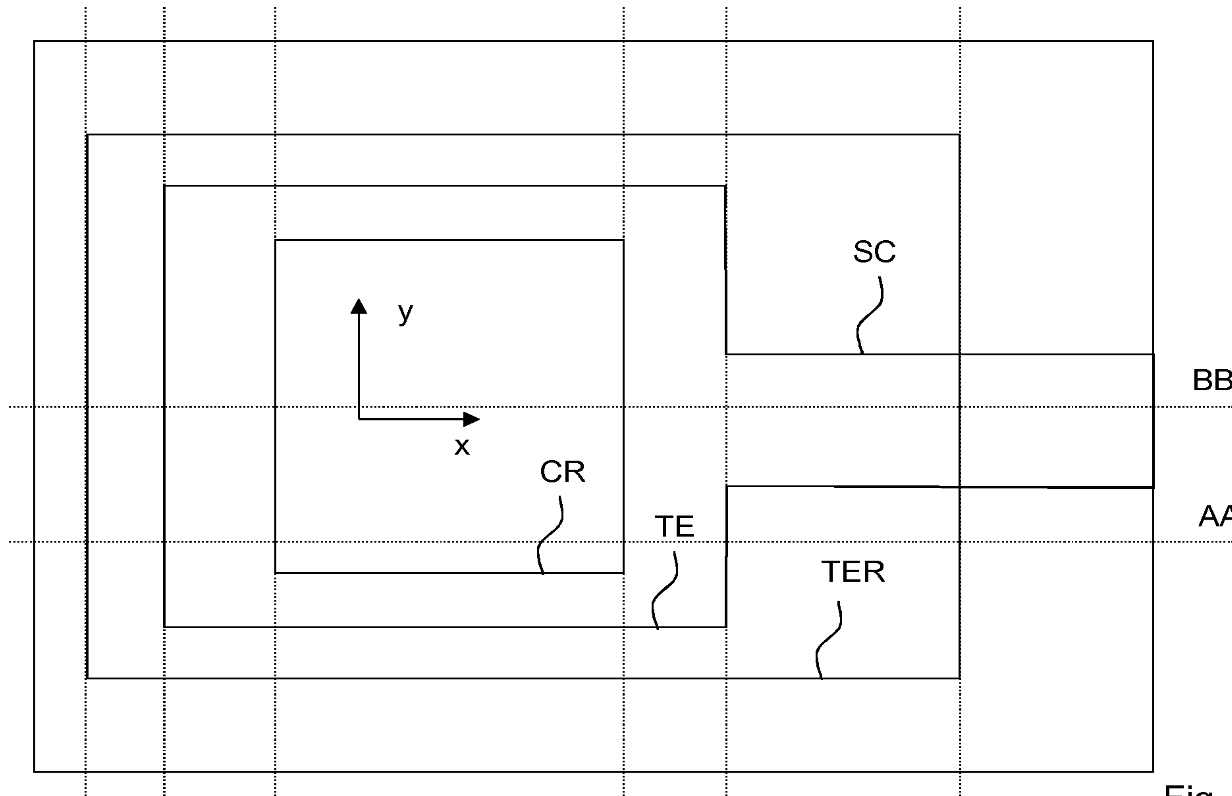

Fig. 2

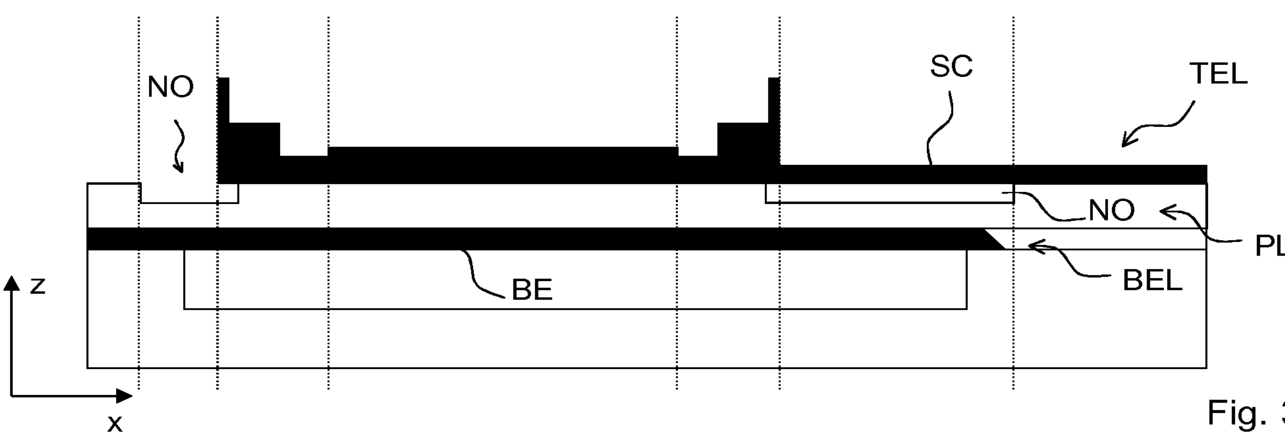

Fig. 3

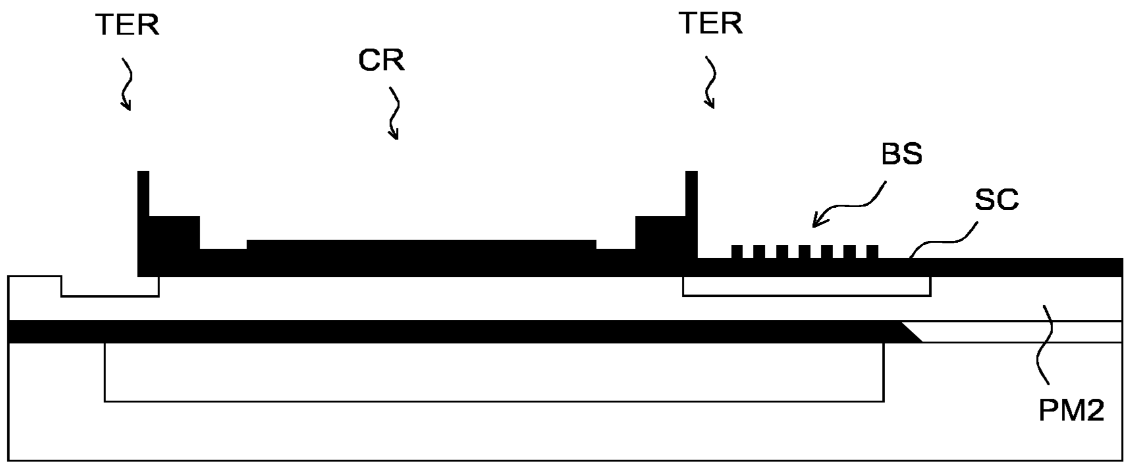

Fig. 4

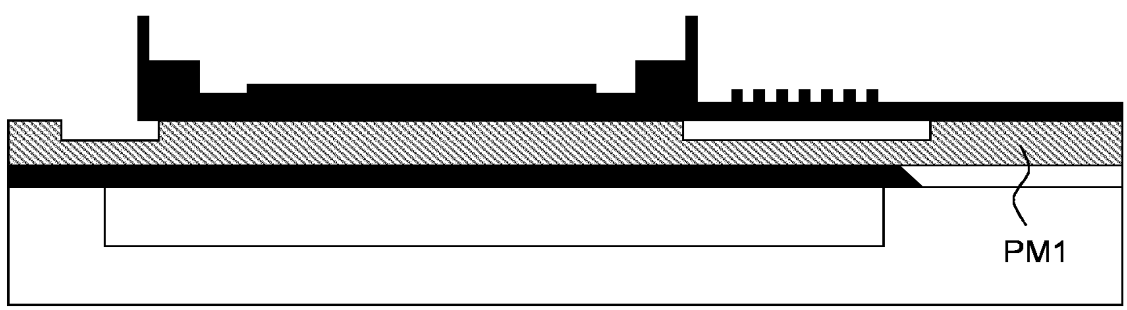

Fig. 5

Fig. 6

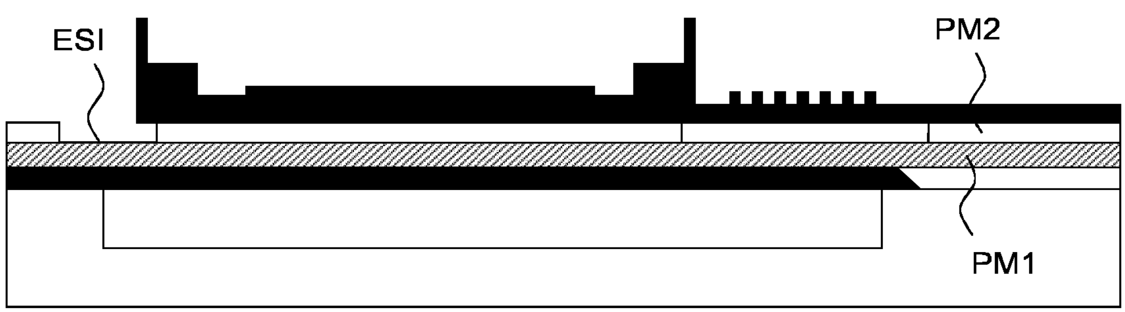

Fig. 7

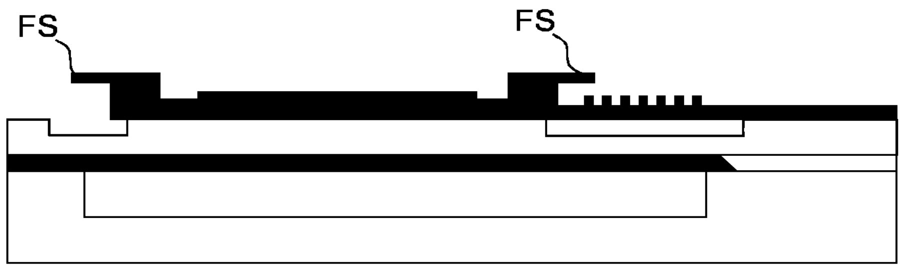

Fig. 8

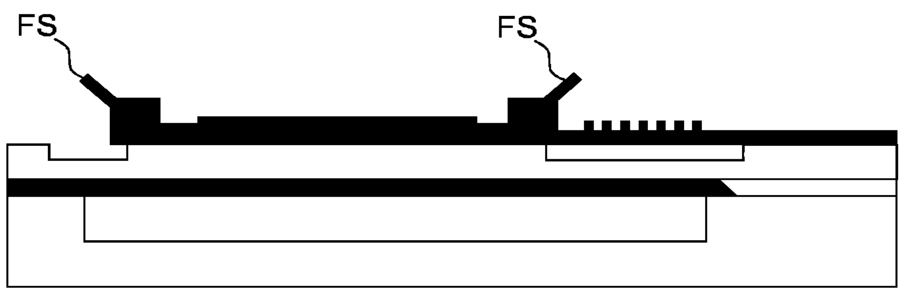

Fig. 9

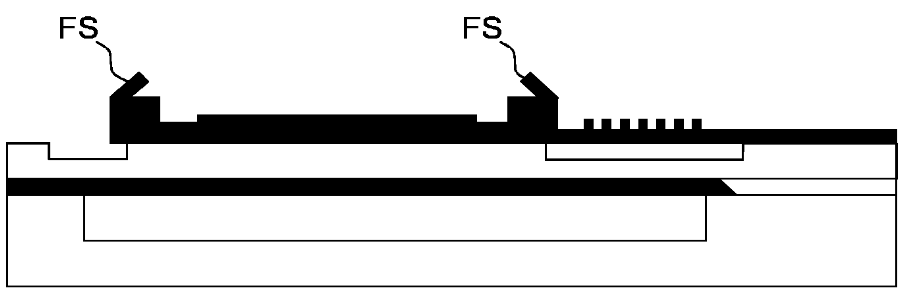

Fig. 10

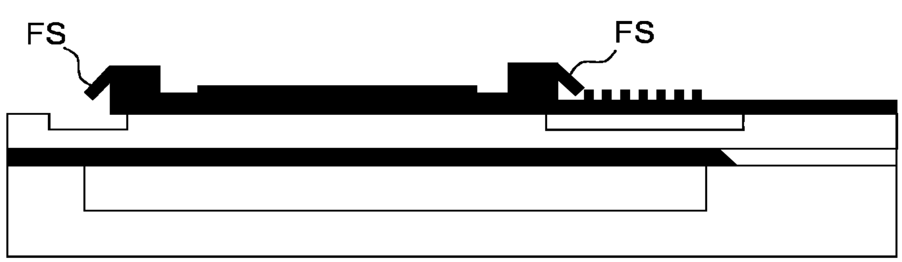

Fig. 11

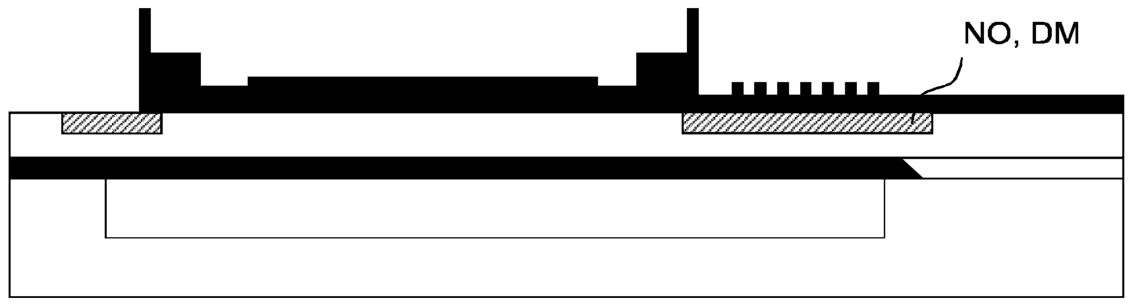

Fig. 12

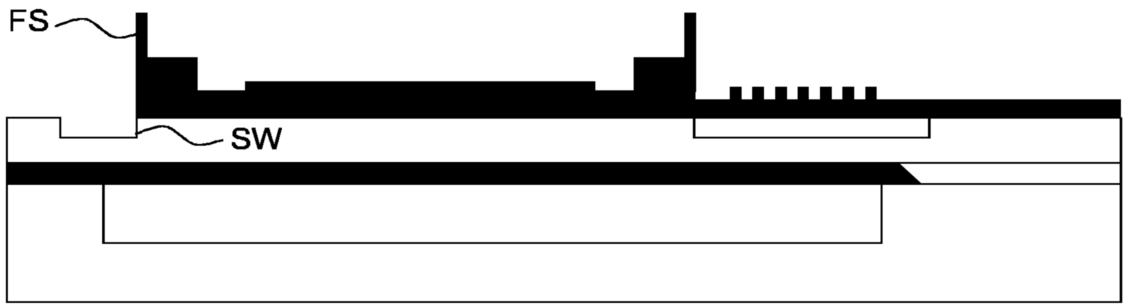

Fig. 13

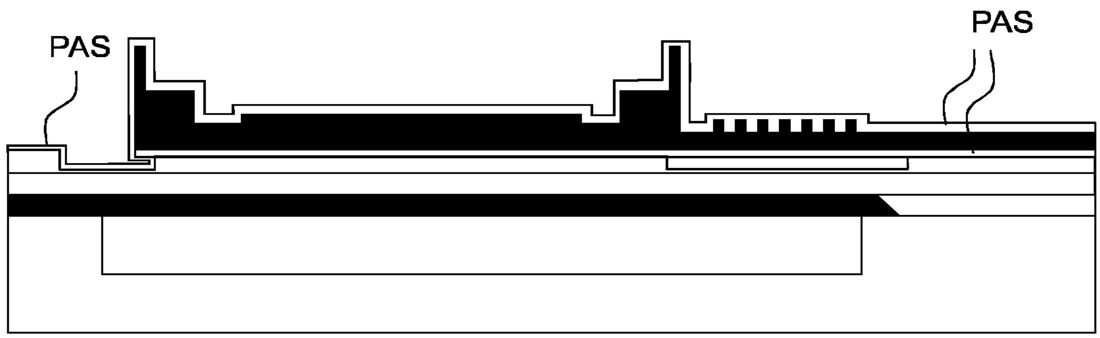

Fig. 14

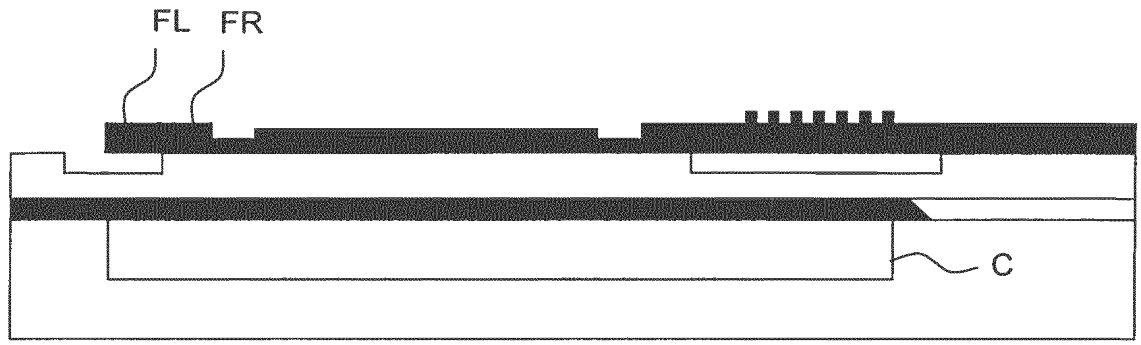

Fig. 15

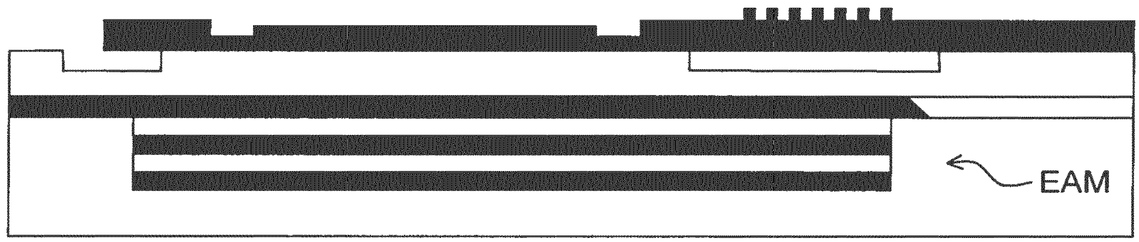

Fig. 16

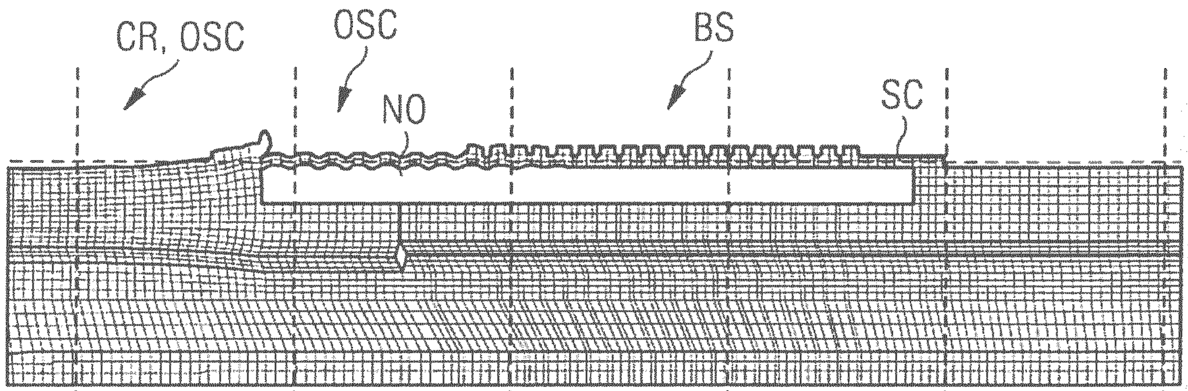

Fig. 17

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/067969

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03H3/02 H03H9/02 H03H9/17 H03H9/13
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 H01L

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

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

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
12 September 2018	24/09/2018

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	Maget, Judith

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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