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DESCRIPTION

TECHNICAL FIELD

[0001] In general, the present application relates to the field of electronic sensors based on surface acoustic wave (SAW) transducers. In particular, the present application relates to the GaN/AlGaN SAW RFID sensor and its use in material and structure sensing.

BACKGROUND

[0002] Surface acoustic-wave (SAW) sensors play an important role in many fields of material sensing and industrial applications. In general, a surface acoustic wave is an acoustic wave that propagates along the surface of a certain (piezoelectric) material. It is generated by interdigitated transducer (IDT) electrodes (or "fingers"), which are special periodic metallic bars deposited on a piezoelectric material. When any sinusoidal wave having a period equal to the period of the IDT electrodes is applied, mechanical vibration occurs beneath the IDT electrodes, thereby generating an acoustic wave, which is perpendicular to the geometry of the IDT bars. This acoustic wave propagates on the surface of the piezoelectric material away from the IDT electrodes in both directions.

[0003] The acoustic wave generated by the IDTs is localised in the surface region and penetrates the bulk piezoelectric material only to a wavelength deep region. That is why the SAW has a very high energy density at the surface, which gives the name "surface acoustic wave". The SAW propagates in a piezoelectric material approximately 10^5 times slower than a regular electromagnetic wave. Consequently, the SAW wavelength in the piezoelectric material is 10^5 times smaller than the wavelength of an electromagnetic wave, making the SAW-based sensor a very compact device.

[0004] Fabrication of the SAW sensors requires either deposition or etching of the metallic IDTs on a piezoelectric material, and it uses the CMOS process technology, which allows a large scale manufacture. The factors that can affect the piezoelectric material surface condition include pressure, temperature, humidity and mass loading. Accordingly, SAW sensors can be used as pressure, temperature, humidity sensors, and as sensors capable of detecting mass changes or electric field alterations at the surface. A MEMS-CMOS technology facilitates the integration of the SAW sensors and their data processing circuits. Specially designed SAW sensors can also be used in a passive mode without need for batteries. An RFID antenna can be added to the input IDT electrode and the signal received by the antenna can then stimulate the SAW used for sensing as mentioned before. These are actually the SAW sensors using RFID tags. The ultrahigh sensitivity, compact nature, ease of fabrication and wireless operation make these sensors very attractive for material sensing.

[0005] Pearton et al (2004) in "Topical Review: GaN-based diodes and transistors for chemical, gas, biological and pressure sensing", Journal of Physics: Condensed Matter 16:29 (2004), pages R961-R994, discloses the use of the AlGaN/GaN heterostructure to implement the SAW sensor and demonstrates that this heterostructure shows a strong dependence of source/drain current in piezoelectric polarization-induced 2DEG channels on variations in electrostatic boundary conditions of the free surface above the channel. However, the structure known from this publication lacks an additional piezoelectrical layer.

[0006] Shigekawa et al (2008) in "Surface Acoustic Waves in Reverse-Biased AlGaN/GaN Heterostructures", IEEE Transactions on Electron Devices 55:7 (2008), pages 1585-1591, examines the properties of the SAWs in reverse-biased AlGaN/GaN heterostructures grown on (0001) sapphire substrates by investigating the characteristics of SAW filters composed of IDTs made of interdigital Schottky and ohmic contacts. Although this publication provides a multilayer heterojunction structure on a piezoelectric sapphire substrate, it does not disclose that the provided heterostructure is a pseudo-conducting heterostructure (as will be discussed hereinbelow).

[0007] CN 105 424 780 A by Beijing Delft Electronic Technology Co. discloses a sensor comprising a heterostructure forming a 2DEG channel, wherein the thickness of the barrier layer is flexibly set in order to improve the detection range of the sensor. In particular, when AlN is used, it is reported that the thickness of the barrier layer is between 2 and 8 nm. However, this publication is not concerned with the enhancement of the sensitivity of the sensor, which is the problem solved by the present invention.

[0008] Lalinsky, T. et al. (2010) in "Surface Acoustic Waves in Reverse-Biased AlGaN/GaN Heterostructures", IEEE TRANSACTIONS ON ELECTRON DEVICES, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 55, no. 7, 1 July 2008 (2008-07-01), pages 1585-1591, discloses providing a multilayer heterojunction structure on a piezoelectric sapphire substrate. However, the document fails to disclose that the heterostructure is a pseudo-conducting heterostructure.

SUMMARY

[0009] The invention is defined by the independent claims. The present application describes embodiments of a microelectronic sensor based on a combination of a two-dimensional electron gas (2DEG) or two-dimensional hole gas (2DHG) conducting structure and surface acoustic wave (SAW) transducer. In some embodiments, the sensor contains a piezoelectric substrate, on which a multilayer heterojunction structure is deposited. This heterojunction structure comprises at least two layers, a buffer layer and a barrier layer, wherein both layers are grown from III-V single-crystalline or polycrystalline semiconductor materials. Interdigitated transducers (IDTs) transducing surface acoustic waves are mounted on the piezoelectric substrate; they may be installed on top of the barrier layer.

[0010] A conducting channel comprising a two-dimensional electron gas (2DEG) or a two-

dimensional hole gas (2DHG) is formed at the interface between the buffer and barrier layers and provides electron or hole current in the system between source and drain electrodes. In a particular embodiment, the heterojunction structure may be a three-layer structure consisting of two buffer layers and one barrier layer squeezed between said buffer layers like in a sandwich. This may lead to formation of the two-dimensional hole gas (2DHG) in the top buffer layer above the barrier layer which results in reversing polarity of the structure. An optional dielectric layer may be deposited on top of the heterojunction structure. The open gate area of the 2DEG/2DHG is formed between the source and drain areas as a result of recessing or growing of the top layer to a specific thickness.

[0011] The IDTs may be made from GaN/AlGaN semiconductor materials and from metal turning the IDTs into the 2DEG/2DHG conducting structures. In a particular embodiment, the piezoelectric substrate may be optionally placed on a GaN/AlGaN free-standing membrane resulting in a SAW-FBAR (Film Bulk Acoustic Resonators) configuration, for achieving ultra-sensitivity. In another embodiment, the sensor may be based on a regular silicon piezoelectric substrate firmly connected to a structural material being tested. In case of any stress or mechanical deformation of this structural material, the piezoelectric GaN/AlGaN stack will also be stressed or deformed, thereby changing the SAW propagation parameters. This is because of the piezoelectric polarization effect within the SAW structures resulting in change of the S21 transfer parameter on the IDT receiver.

[0012] The source and drain non-ohmic (i.e. capacitively-coupled) contacts are connected to the 2DEG/2DHG channel and to electrical metallizations, the latter are placed on top of the sensor and connect it to an electric circuit of the sensor. Since the source and drain contacts are non-ohmic, the DC readout cannot be carried out. In order to electrically contact the 2DEG/2DHG channel underneath, about 5-20 nm below the metallizations, the AC-frequency regime must be used. In other words, the AC readout or impedance measurements of the electric current flowing through the 2DEG/2DHG-channel should be performed in this particular case. The capacitive coupling of the non-ohmic metal contacts with the 2DEG/2DHG channel is normally induced at the frequency higher than 30 kHz.

[0013] In some embodiments, the multilayer heterojunction substrate of the present application may be grown from any available III-V single-crystalline or polycrystalline semiconductor materials, for example, GaN/AlGaN, GaN/AlN, GaN/InN, GaN/InAlN, InN/InAlN, GaN/InAlGaN, GaAs/AlGaAs and LaAlO₃/SrTiO₃. In a specific case of the substrate grown from GaN/AlGaN, it has been experimentally and surprisingly found that the highest sensitivity of the sensor is achieved when thickness of the top recessed layer (GaN buffer layer or AlGaN barrier layer) in the open gate area between the source and drain contacts is 5-9 nm, preferably 6-7 nm, more preferably 6.2-6.4 nm. This recessed layer thickness corresponds to the pseudo-conducting current range between normally-on and normally-off operation mode of the 2DEG/2DHG conducting channel. In addition, surface roughness of the top recessed layer within the open gate area between the source and drain contacts has a roughness of about 0.2 nm or less, preferably 0.1 nm or less, more preferably 0.05 nm.

[0014] Further, in some embodiments, the present application provides the zero-power SAW RFID sensor, which is based on the GaN/AlGa_N heterostructure, and its use in material and structure sensing. In another embodiment, the sensor is a zero-power sensor remotely powered with the RF-energy and RFID-coded via the orthogonal frequency coding (OFC) method.

[0015] Various embodiments may allow various benefits, and may be used in conjunction with various applications. The details of one or more embodiments are set forth in the accompanying figures and the description below. Other features, objects and advantages of the described techniques will be apparent from the description and drawings and from the claims

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Disclosed embodiments will be understood and appreciated more fully from the following detailed description taken in conjunction with the appended figures. The drawings included and described herein are schematic and are not limiting the scope of the disclosure. It is also noted that in the drawings, the size of some elements may be exaggerated and, therefore, not drawn to scale for illustrative purposes. The dimensions and the relative dimensions do not necessarily correspond to actual reductions to practice of the disclosure.

Fig. 1 schematically shows the quantum well at three different biasing conditions:

Fig. 1a: positive gate potential ($+V_G$) is much higher than threshold voltage (V_T),

Fig. 1b: 0V gate potential, and

Fig. 1c: negative gate potential ($-V_G$) is below threshold voltage (V_T).

Fig. 2 schematically shows the dependence of the source-drain current (a charge carrier density) induced inside the 2DEG channel of a GaN/AlGa_N HEMT on the thickness of the AlGa_N barrier layer recessed in the open gate area.

Fig. 3 illustrates a theory behind the 2DEG formation (charge neutrality combined with the lowest energy level) at the conduction band discontinuity.

Fig. 4 schematically shows the formation of the 2DEG and 2DHG conducting channels in the Ga-face three-layer AlGa_N/Ga_N PC-HEMT structure.

Fig. 5 schematically shows the formation of the 2DEG and 2DHG conducting channels in the N-face three-layer AlGa_N/Ga_N PC-HEMT structure.

Fig. 6 schematically shows the formation of the 2DEG conducting channel in the N-face three-layer AlGa_N/Ga_N PC-HEMT structure with an ultrathin Al(Ga_N)_N layer for improved confinement.

Fig. 7a schematically shows the input interdigitated transducer (IDT)-based SAW device.

Fig. 7b schematically shows the IDT and its characteristic parameters: length (L), width (W) and acoustic wavelength (λ).

Fig. 7c shows the bandwidth (B) of the SAW as a function of the number of the IDTs and the frequency (f), where f_0 is the centre frequency.

Fig. 8 schematically shows a SAW RFID sensor of an embodiment with 2DEG IDTs on a GaN/AlGaIn heterostructure.

Figs. 9a-9c schematically show a basic topology of the sensor of an embodiment with free standing membranes, wherein lines (100) show the metal IDT structures, area (102) shows the PC-HEMT-like structure and area (103) shows the GaN/AlGaIn-layered substrate.

Figs. 10a-10b schematically show a basic topography of the 2DEG-FBAR-SAW sensor configuration of an embodiment with a thin resonating film (104) on top of the substrate.

Fig. 11 shows the photolithographic layout masks of the 2DEG-based SAW resonator using the standard configuration with two symmetrical IDT structures (fingers).

Fig. 12 shows the SEM images from several different IDT layouts of the SAW resonators fabricated via the lift-off/or ion-milling patterning technique.

Fig. 13 shows the microscope images of the fabricated SAW resonators of **Figs. 11-12** on the free-standing GaN/AlGaIn membranes having the unstructured 2DEG with the DRIE-removed Si substrate.

Fig. 14 schematically shows a method for non-destructive detection of the pipe content and monitoring the structural pipe material health with an ultrasensitive microphone of an embodiment.

Fig. 15a shows a microscope image of the ultrasensitive microphone of an embodiment.

Fig. 15b schematically shows a sensor of an embodiment comprising the SAW resonator chip and the meander antenna generating the SAW on the chip surface.

Fig. 16 shows the microscope images of the SAW resonators as in **Fig. 11**, and further highlights the free-standing FBAR membrane in the FBAR-SAW configuration of the sensor.

Fig. 17 schematically shows a zero-power SAW RFID sensor of an embodiment for material and structure sensing with a remote readout.

Fig. 18 schematically shows an optoelectronic sensor of an embodiment for material and structure sensing with a remote readout.

Fig. 19 shows the experimental S21-transfer parameter measured with the ultrasensitive microphone of an embodiment.

DETAILED DESCRIPTION

[0017] In the following description, various aspects of the present application will be described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the present application. However, it will also be apparent to one skilled in the art that the present application may be practiced without the specific details presented herein. Furthermore, well-known features may be omitted or simplified in order not to obscure the present application.

[0018] The term "comprising", used in the claims, is "open ended" and means the elements recited, or their equivalent in structure or function, plus any other element or elements which are not recited. It should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements or steps. It needs to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression "a device comprising x and z" should not be limited to devices consisting only of components x and z. Also, the scope of the expression "a method comprising the steps x and z" should not be limited to methods consisting only of these steps.

[0019] Unless specifically stated, as used herein, the term "about" is understood as within a range of normal tolerance in the art, for example within two standard deviations of the mean. In one embodiment, the term "about" means within 10% of the reported numerical value of the number with which it is being used, preferably within 5% of the reported numerical value. For example, the term "about" can be immediately understood as within 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, 1%, 0.5%, 0.1%, 0.05%, or 0.01% of the stated value. In other embodiments, the term "about" can mean a higher tolerance of variation depending on for instance the experimental technique used. Said variations of a specified value are understood by the skilled person and are within the context of the present invention. As an illustration, a numerical range of "about 1 to about 5" should be interpreted to include not only the explicitly recited values of about 1 to about 5, but also include individual values and sub-ranges within the indicated range. Thus, included in this numerical range are individual values such as 2, 3, and 4 and sub-ranges, for example from 1-3, from 2-4, and from 3-5, as well as 1, 2, 3, 4, 5, or 6, individually. This same principle applies to ranges reciting only one numerical value as a minimum or a maximum. Unless otherwise clear from context, all numerical values provided herein are modified by the term "about". Other similar terms, such as "substantially", "generally", "up to" and the like are to be construed as modifying a term or value such that it is not an absolute. Such terms will be defined by the circumstances and the terms that they modify as those terms are understood by those of skilled in the art. This includes, at very least, the degree of expected experimental error, technical error and instrumental error for a given experiment, technique or an instrument used to measure a value.

[0020] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items. Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the specification and relevant art and should not be interpreted in an idealized or overly formal sense unless expressly so defined herein. Well-known functions or constructions may not be described in detail for brevity and/or clarity.

[0021] It will be understood that when an element is referred to as being "on", "attached to", "connected to", "coupled with", "contacting", etc., another element, it can be directly on, attached to, connected to, coupled with or contacting the other element or intervening elements may also be present. In contrast, when an element is referred to as being, for example, "directly on", "directly attached to", "directly connected to", "directly coupled" with or "directly contacting" another element, there are no intervening elements present. It will also be appreciated by those of skill in the art that references to a structure or feature that is disposed "adjacent" another feature may have portions that overlap or underlie the adjacent feature.

[0022] The polarization doped high-electron-mobility transistor (HEMT) is a field effect transistor (FET) in which two layers of different bandgap and polarisation field are grown upon each other forming the heterojunction structure. In one aspect, the sensor of the present application contains a piezoelectric substrate comprising the HEMT-like multilayer heterojunction structure. This structure is essentially based on at least two layers of III-V semiconductor materials, such as gallium nitride (GaN) and aluminium gallium nitride (AlGaN). As a consequence of the discontinuity in the polarisation field, surface charges are created at the interface between the layers of the heterojunction structure. If the induced surface charge is positive, electrons will tend to compensate the induced charge resulting in the formation of the channel. Since the channel electrons are confined in a quantum well in an infinitely narrow spatial region at the interface between the layers, these electrons are referred to as a two-dimensional electron gas (2DEG). This special confinement of the channel electrons in the quantum well actually grants them two-dimensional features, which strongly enhance their mobility surpassing the bulk mobility of the material in which the electrons are flowing.

[0023] **Figs. 1a-1c** schematically shows the quantum well at three different biasing conditions starting from the positive gate potential (V_G), much higher than the threshold voltage (V_T), and going down to the 0V gate potential and further to the negative values below the threshold voltage. The V_T is defined as a voltage, which is required to populate electrons at the interface between the GaN layer and the AlGaN layers, thereby creating conductivity of the 2DEG channel. Since the 2DEG channel electrons occupy energy levels below the Fermi level, the Fermi level in a quantum well is located above several energy levels when $V_G \gg V_T$ (**Fig. 1a**). This enables high population of channel electrons and consequently, high conductivity. The 2DEG channel is turned on in this case. However, when V_G decreases to 0V (**Fig. 1b**), the

Fermi level also drops with respect to the quantum well. As a result, much fewer electron energy levels are populated and the amount of the 2DEG channel electrons significantly decreases. When V_G much less than V_T (**Fig. 1c**), all electron energy levels are above the Fermi level, and there is no the 2DEG electrons below the gate. This situation is called "channel depletion", and the channel is turned off.

[0024] Many commercially available HEMTs based on the layers of III-V semiconductor materials have a negative value of V_T , resulting in a "normally-on" operation mode at 0V gate potential. They are called "depletion-mode" semiconductor transistors and used in various power switching applications when the negative voltage must be applied on the gate in order to block the current. However, for safe operation at high voltage or high power density, in order to reduce the circuit complexity and eliminate standby power consumption, the transistors with "normally-off" characteristics are preferred. The high voltages and high switching speeds allow smaller, more efficient devices, such as home appliances, communications and automobiles to be manufactured. To control the density of electrons in the 2DEG channel and to switch the HEMT on and off, the voltage at the gate of the transistor is normally regulated.

[0025] Several techniques to manufacture the normally-off semiconductor structures have been reported. Burnham *et al* (2010) proposed normally-off structures of the recessed gate type. In this structure, the AlGa_N barrier layer is etched and the gate is brought closer to the interface between the AlGa_N barrier layer and the Ga_N buffer layer. As the gate approaches the interface between the layers, the V_T increases. Thus, the normally-off operation of the 2DEG conducting channel is achieved once the depletion region reaches the interface and depletes the 2DEG channel at zero gate voltage. The major advantages of these structures are relatively lower power consumption, lower noise and simpler drive circuits. They are currently used, for example, in microwave and millimetre wave communications, imaging and radars.

[0026] Chang *et al* (2009) proposed instead of etching the relatively thick barrier layer to approach the AlGa_N/Ga_N interface, to use a very thin AlGa_N barrier. This structure also achieves the normally-off operation of the 2DEG channel by approaching the gate towards the AlGa_N/Ga_N interface. Chen *et al* (2010) proposed to use the fluorine-based plasma treatment method. Although many publications have adopted various methods to achieve normally-off devices with minimum impact on the drain current, they unfortunately sacrificed device turn-on performance.

[0027] **Fig. 2** shows the dependence of the source-drain current (a charge carrier density) on the recessed barrier layer thickness. As seen from the plot, structures that have a thickness of the barrier layer larger than 9 nm form normally-on 2DEG channels. In such structures, due to the inherent polarisation effects present in the III-V materials, a thin sheet of charges is induced at the top and bottom of the interfaces of the barrier layer. As a result, a high electric field is induced in the barrier layer, and surface donor states at the top interface start donating electrons to form the 2DEG channel at the proximity of the hetero-junction interface without the application of a gate bias. These structures therefore constitute normally-on devices. On the

other hand, the structures that have a thickness of the barrier layer lower than about 5 nm constitute normally-off devices.

[0028] The present application describes embodiments of a microelectronic sensor or sensor chip based on a combination of a two-dimensional electron gas (2DEG) or two-dimensional hole gas (2DHG) structure and surface acoustic wave (SAW) transducer. The sensor contains a piezoelectric substrate, on which the multilayer heterojunction structure may be deposited. This heterojunction structure comprises at least two layers, a buffer layer and a barrier layer, wherein both layers are grown from the aforementioned III-V single-crystalline or polycrystalline semiconductor materials. Interdigitated transducers (IDTs) transducing surface acoustic waves may be installed on top of the barrier layer. The multilayer heterojunction structure of the present invention is grown from GaN/AlGaN. In this case of the substrate grown from GaN/AlGaN, it has been experimentally found that the highest sensitivity of the sensor is achieved when the thickness of the top recessed layer (GaN buffer layer or AlGaN barrier layer) in the open gate area between the source and drain contacts is 5-9 nm, preferably 6-7 nm, more preferably 6.2-6.4 nm. In addition, it was also found that the sensor exhibits its highest sensitivity when surface roughness of the top recessed layer is about 0.2 nm or less, preferably 0.1 nm or less, more preferably 0.05 nm.

[0029] Thus, the top layer recessed or grown in the open gate area to 5-9 nm must be optimised for significantly enhancing sensitivity of the sensor. This specific thickness of the barrier layer was surprisingly found to correspond to the "pseudo-conducting" current range between normally-on and normally-off operation modes of the 2DEG channel and requires further explanation.

[0030] "Pseudo-contacting" (to distinguish from normally-conducting) current range of the 2DEG channel is defined as an operation range of the channel between its normally-on and normally-off operation modes. "Trap states" are states in the band-gap of a semiconductor which trap a carrier until it recombines. "Surface states" are states caused by surface reconstruction of the local crystal due to surface tension caused by some crystal defects, dislocations, or the presence of impurities. Such surface reconstruction often creates "surface trap states" corresponding to a surface recombination velocity. Classification of the surface trap states depends on the relative position of their energy level inside the band gap. The surface trap states with energy above the Fermi level are acceptor-like, attaining negative charge when occupied. However, the surface trap states with energy below the Fermi level are donor-like, positively charged when empty and neutral when occupied. These donor-like surface trap states are considered to be the source of electrons in the formation of the 2DEG channel. They may possess a wide distribution of ionization energies within the band gap and are caused by redox reactions, dangling bonds and vacancies in the surface layer. A balance always exists between the 2DEG channel density and the number of ionised surface donors which is governed by charge neutrality and continuity of the electric field at the interfaces.

[0031] Thus, the donor-like surface traps at the surface of the barrier layer are one of the most important sources of the 2DEG in the channel. However, this only applies for a specific barrier

layer thickness. In a relatively thin barrier layer, the surface trap state is below the Fermi level. However, as the barrier layer thickness increases, the energy of the surface trap state approaches the Fermi energy until it coincides with it. The thickness of the barrier layer corresponding to such situation is defined as "critical". At this point, electrons filling the surface trap state are pulled to the channel by the strong polarisation-induced electric field found in the barrier to form the 2DEG instantly.

[0032] If the surface trap states are completely depleted, further increase in the barrier layer thickness will not increase the 2DEG density. Actually, if the 2DEG channel layer fails to stretch the barrier layer, the later will simply relax. Upon relaxation of the barrier layer, many crystal defects are created at the interface between the buffer and barrier layers, and the piezoelectric polarisation instantly disappears causing deterioration in the 2DEG density.

[0033] In order to illustrate the above phenomenon of the pseudo-conducting current, reference is now made to **Figs. 2** and **3**. As described above, **Fig. 2** shows the dependence of the source-drain current (a charge carrier density) on the recessed AlGa_N barrier layer thickness. Energy equilibrium between the donor surface trap states and AlGa_N tunnel barrier leads to the 2DEG formation (charge neutrality combined with the lowest energy level) at the conduction band discontinuity. As explained above, decrease in the thickness of the barrier layer results in increase of the energy barrier. As a result, the ionisable donor-like surface trap states, which are responsible for electron tunnelling from the surface to 2DEG, drift below the Fermi level, thereby minimizing the electron supply to the 2DEG channel. This theoretical situation is further illustrated in **Fig. 3**. Therefore, the recess of the AlGa_N layer from 9 nm to 5 nm leads to huge drop in conductivity of the two-dimensional electron gas for six orders of magnitude.

[0034] Thus, the mechanism of the 2DEG depletion based on recessing the barrier layer is strongly dependent on the donor-like surface trap states (or total surface charge). As the thickness of the barrier layer decreases, less additional external charge is needed to apply to the barrier layer surface in order to deplete the 2DEG channel. There is a critical (smallest) barrier thickness, when the 2DEG channel is mostly depleted but still highly conductive due to a combination of the energy barrier and the donor surface trap states energy. At this critical thickness, even the smallest energy shift at the surface via any external influence, for example an acoustic wave propagating along the surface, leads immediately to the very strong 2DEG depletion. As a result, the surface of the barrier layer at this critical thickness is extremely sensitive to any smallest change in the electrical field of the surroundings.

[0035] Thus, recess of the barrier layer from 9 nm down to 5 nm significantly reduced the 2DEG density, brought the sensor to the "near threshold" operation and resulted in highly increased surface charge sensitivity. The specific 5-9 nm thickness of the barrier layer responsible for the pseudo-conducting behaviour of the 2DEG channel gives the sensor an incredible sensitivity.

[0036] In addition to the recessed or grown top barrier layer thickness, roughness of the

barrier layer surface is another very important parameter that has not been previously disclosed. It has been surprisingly found that the roughness of the AlGa_N barrier layer surface below 0.2 nm prevents scattering of the donor-like surface trap states.

[0037] Thus, combination of these two features: 5-9 nm thickness of the AlGa_N barrier layer and strongly reduced roughness of its surface make the sensor incredibly sensitive.

[0038] In a further aspect, the hetero-junction structure may be a three-layer structure consisting of two buffer layers and one barrier layer squeezed between said buffer layers like in a sandwich, wherein the top layer is a buffer layer. This may lead to formation of the two-dimensional hole gas (2DHG) in the top buffer layer above the barrier layer which results in reversing polarity of the transistor compared to the two-layer structure discussed above.

[0039] In general, polarity of III-V nitride semiconductor materials strongly affects the performance of the transistors based on these semiconductors. The quality of the wurtzite Ga_N materials can be varied by their polarity, because both the incorporation of impurities and the formation of defects are related to the growth mechanism, which in turn depends on surface polarity. The occurrence of the 2DEG/2DHG and the optical properties of the hetero-junction structures of nitride-based materials are influenced by the internal field effects caused by spontaneous and piezo-electric polarizations. Devices in all of the III-V nitride materials are fabricated on polar {0001} surfaces. Consequently, their characteristics depend on whether the Ga_N layers exhibit Ga-face positive polarity or N-face negative polarity. In other words, as a result of the wurtzite Ga_N materials polarity, any Ga_N layer has two surfaces with different polarities, a Ga-polar surface and an N-polar surface. A Ga-polar surface is defined herein as a surface terminating on a layer of Ga atoms, each of which has one unoccupied bond normal to the surface. Each surface Ga atom is bonded to three N atoms in the direction away from the surface. In contrast, an N-polar surface is defined as a surface terminating on a layer of N atoms, each of which has one unoccupied bond normal to the surface. Each surface N atom is also bonded to three Ga atoms in the direction away from the surface. Thus, the N-face polarity structures have the reverse polarity to the Ga-face polarity structures.

[0040] As described above for the two-layer heterojunction structure, the barrier layer is always placed on top of the buffer layer. The layer which is therefore recessed is the barrier layer, specifically the AlGa_N layer. As a result, since the 2DEG is used as the conducting channel and this conducting channel is located slightly below the barrier layer (in a thicker region of the Ga_N buffer layer), the hetero-junction structure is grown along the {0001}-direction or, in other words, with the Ga-face polarity. However, as explained above, the physical mechanism that leads to the formation of the 2DEG is a polarisation discontinuity at the AlGa_N/Ga_N interface, reflected by the formation of the polarisation-induced fixed interface charges that attract free carriers to form a two-dimensional carrier gas. It is a positive polarisation charge at the AlGa_N/Ga_N interface that attracts electrons to form 2DEG in the Ga_N layer slightly below this interface.

[0041] As noted above, polarity of the interface charges depends on the crystal lattice

orientation of the hetero-junction structure, i.e. Ga-face versus N-face polarity, and the position of the respective AlGa_N/Ga_N interface in the hetero-junction structure (above or below the interface). Therefore, different types of the accumulated carriers can be present in the hetero-junction structure of the embodiments.

[0042] In case of the three-layer hetero-junction structure, there are four possible configurations:

Ga-face polarity

1. 1) The Ga-face polarity is characterised by the 2DEG formation in the Ga_N layer below the AlGa_N barrier layer. This is actually the same two-layer configuration as described above, but with addition of the top Ga_N layer. In this configuration, the AlGa_N barrier layer and two Ga_N buffer layers must be nominally undoped or n-type doped.
2. 2) In another Ga-face configuration shown in **Fig. 4**, in order to form the conducting channel comprising a two-dimensional hole gas (2DHG) in the top Ga_N layer above the AlGa_N barrier layer in the configuration, the AlGa_N barrier layer should be p-type doped (for example, with Mg or Be as an acceptor) and the Ga_N buffer layer should be also p-type doped with Mg, Be or intrinsic.

N-face polarity

- 3) The N-face polarity is characterised by the 2DEG formation in the top Ga_N layer above the AlGa_N barrier layer, as shown in **Fig. 5**. In this case, the AlGa_N barrier layer and two Ga_N buffer layers must be nominally undoped or n-type doped.
- 4) The last configuration assumes that the 2DHG conducting channel is formed in the buffer Ga_N layer below the AlGa_N barrier layer. The top Ga_N layer may be present (three-layer structure) or not (two-layer structure) in this case. The AlGa_N barrier layer must be p-type doped (for example, with Mg or Be as an acceptor) and the bottom Ga_N layer should be also p-type doped with Mg, Be or intrinsic.

[0043] Thus, there are four hetero-junction three-layer structures implemented in the transistor of the embodiments, based on the above configurations:

1. A. **Ga-Face** Ga_N/AlGa_N/Ga_N heterostructure with the 2DEG formed in the Ga_N buffer layer below the AlGa_N barrier layer. In this case, the top Ga_N layer may be omitted to obtain the two-layer structure. For the three-layer structure, the top Ga_N layer must be recessed to 1-9 nm thickness in the open gate area or grown with this low thickness, with the roughness below 0.2 nm, and the thickness of the AlGa_N barrier can be adjusted properly during growth
2. B. **Ga-Face** Ga_N/AlGa_N/Ga_N heterostructure with the 2DHG conducting channel formed in the top Ga_N layer above the AlGa_N barrier layer. The top Ga_N layer must be recessed to 5-9 nm thickness in the open gate area with the roughness below 0.2 nm,

and the thickness of the AlGaN barrier layer can be adjusted properly. P-type doping concentrations of the GaN layer and AlGaN barrier have to be adjusted; the 2DHG has to be contacted (in the ideal case by ohmic contacts).

3. C. **N-Face** GaN/AlGaN/GaN heterostructure with the 2DEG in the top GaN layer above the AlGaN barrier layer. The top GaN layer must be recessed to 5-9 nm thickness in the open gate area with the roughness below 0.2 nm. Thickness of the AlGaN barrier can be adjusted during growth. N-type doping levels of the GaN buffer layer and the AlGaN barrier layer must be adjusted; the 2DEG has to be contacted (in the ideal case by ohmic contacts).
4. D. **N-Face** GaN/AlGaN/GaN heterostructure with the 2DHG in the GaN buffer layer below the AlGaN barrier layer. In this case, the top GaN layer may be omitted to obtain the two-layer structure. In both, the two-layer and three-layer configurations, the top GaN layer must be recessed to 1-9 nm thickness in the open gate area with the roughness below 0.2 nm, and the thickness of the AlGaN barrier can be adjusted properly.

[0044] In all the above structures, the deposition of a dielectric layer on top might be beneficial or even necessary to obtain a better confinement (as in case of the N-face structures). As shown in **Fig. 6**, for the above "C" structure, it may be even more beneficial to include an ultrathin (about 1 nm) AlN or AlGaN barrier layer with high Al-content on top of the 2DEG channel to improve the confinement.

[0045] The preferable structures of the embodiments are structures "B" and "C". In the structure "B", the 2DHG conducting channel formed in the top GaN layer, which has a higher chemical stability (particularly towards surface oxidation) than the AlGaN layer. Concerning the structure "C", the 2DEG conducting channel might be closer to the surface. Therefore, the electron mobility might be lower than in the 2DEG structure with the Ga-face polarity. In general, the polarity of the heterostructure can be adjusted by the choice of the substrate (e.g. C-face SiC) or by the growth conditions.

[0046] Another important feature of the sensor of the present application is that an electrical connection of the heterojunction structure to the 2DEG or 2DHG channel is realised via capacitive coupling to the electrical metallizations through a Schottky barrier contact. "Capacitive coupling" is defined as an energy transfer within the same electric circuit or between different electric circuits by means of displacement currents induced by existing electric fields between circuit/s nodes. In general, ohmic contacts are the contacts that follow Ohm's law, meaning that the current flowing through them is directly proportional to the voltage. Non-ohmic contacts however do not follow the same linear relationship of the Ohm's law. In other words, electric current passing through non-ohmic contacts is not linearly proportional to voltage. Instead, it gives a steep curve with an increasing gradient, since the resistance in that case increases as the electric current increases, resulting in increase of the voltage across non-ohmic contacts. This is because electrons carry more energy, and when

they collide with atoms in the conducting channel, they transfer more energy creating new high-energy vibrational states, thereby increasing resistance and temperature.

[0047] When electrical metallizations are placed over single-crystalline or polycrystalline semiconductor material, the "Schottky contact" or "Schottky barrier contact" between the metal and the semiconductor occurs. Energy of this contact is covered by the Schottky-Mott rule, which predicts the energy barrier between a metal and a semiconductor to be proportional to the difference of the metal-vacuum work function and the semiconductor-vacuum electron affinity. However, this is an ideal theoretical behaviour, while in reality most interfaces between a metal and a semiconductor follow this rule only to some degree. The boundary of a semiconductor crystal abrupt by a metal creates new electron states within its band gap. These new electron states induced by a metal and their occupation push the centre of the band gap to the Fermi level. This phenomenon of shifting the centre of the band gap to the Fermi level as a result of a metal-semiconductor contact is defined as "Fermi level pinning", which differs from one semiconductor to another. If the Fermi level is energetically far from the band edge, the Schottky contact would preferably be formed. However, if the Fermi level is close to the band edge, an ohmic contact would preferably be formed. The Schottky barrier contact is a rectifying non-ohmic contact, which in reality is almost independent of the semiconductor or metal work functions.

[0048] Thus, a non-ohmic contact allows electric current to flow only in one direction with a non-linear current-voltage curve that looks like that of a diode. On the contrary, an ohmic contact allows electric current to flow in both directions roughly equally within normal device operation range, with an almost linear current-voltage relationship that comes close to that of a resistor (hence, "ohmic").

[0049] Since the source and drain contacts are non-ohmic (i.e. capacitively-coupled), the DC readout cannot be carried out. To electrically contact the 2DEG/2DHG channel underneath, about 5-20 nm below the metallizations, the AC-frequency regime must be used. In other words, the AC readout or impedance measurements of the electric current flowing through the 2DEG/2DHG-channel should be performed in this particular case. The capacitive coupling of the non-ohmic metal contacts with the 2DEG/2DHG channel becomes possible only if sufficiently high AC frequency, higher than 30 kHz, is applied to the metallizations. To sum up, the electrical metallizations, which are capacitively coupled to the 2DEG/2DHG channel utilise the known phenomenon of energy transfer by displacement currents. These displacement currents are induced by existing electrical fields between the electrical metallizations and the 2DEG/2DHG conducting channel operated in the AC frequency mode through the Schottky contact as explained above.

[0050] Surface acoustic wave (SAW) resonators are a class of MEMS based on the modulation of surface acoustic waves. The detection mechanism for SAW resonators utilizes changes in the amplitude, velocity, or phase of a SAW propagating along the substrate due to changes to the characteristics of the propagation path. In general, the energy of the SAW is normally concentrated in a surface region with a thickness of less than 1.5 times its wavelength.

Therefore, the SAW resonator is extremely sensitive to its environment.

[0051] The principle of the inter-digitated transducer (IDT)-based SAW sensor is shown in **Figs. 7a-7c**. It relies on two IDTs - one to launch and the other to detect a wave that travels from one end of the piezoelectric substrate to the other. A pair of IDTs, fabricated on the GaN/AlGaN substrate, serves as input and output ports of the signals. Fabrication of the SAW sensors comprises material selection, patterning, dicing, surface functionalisation and final packaging. The SAW sensors are fabricated from piezoelectric materials, typically quartz. Each IDT is composed of many pairs of photolithographically defined fingers, wherein each finger is only a few micrometres wide.

[0052] The SAW is extremely sensitive to tiny mass changes and capable of detecting as few as 100 picogram/cm² amount of an analyte, which corresponds to sensitivity to less than 0.01 monolayer of carbon. The velocity and the attenuation of acoustic waves result from changes in surface mass in SAW devices. Measuring both these properties simultaneously helps determine the nature and cause of the sensor response. In general, the SAW sensors are designed by choosing the desired frequency and bandwidth of operation.

[0053] The SAW can be expressed as a complex value $\gamma = \alpha + i\beta$, wherein the given or calculated attenuation constant α and propagation constant $\beta = 2\pi / \lambda$ are important design parameters of the SAW sensor (λ is the acoustic wavelength). Another important design parameter is the electromechanical coupling coefficient K^2 , which is a measure of the efficiency for converting an applied microwave signal into mechanical energy. These parameters will determine the magnitude of the observed changes in the SAW phase velocity and attenuation of the SAW intensity.

[0054] As shown in **Figs. 7b-7c**, the operation frequency of the SAW sensor f_0 can be chosen by properly choosing the inter-digital finger spacing d such that $f_0 = v / d$, where v is the wave propagation velocity in the specific substrate. Consequently, the dimensions of the designed SAW sensor depend on the chosen operating frequency, which can vary from a micrometre for 1-10 GHz to millimetres for kHz-MHz operation. SAW sensors operating in the GHz range can be readily designed and easily integrated with RF, the diverse MMIC, and the microstrip circuits for low power wireless remote sensing. The bandwidth of the acoustic wave is given by $B = v / 2Nd$, where N is number of inter-digital fingers, as shown in **Fig. 7b**.

[0055] The aforementioned GaN/AlGaN-based substrates are almost ideal materials for the SAW sensors due to their high SAW propagation velocity of about 4000 m/s, high electromechanical coupling coefficients, and their compatibility with the RF electronic integration. These materials also show excellent resistance to humidity and chemical etching. The GaN/AlGaN heterostructures described above exhibit a strong piezoelectric effect and have been used to fabricate the ultra-sensitive SAW-microbalances, exploiting the influence of mass accumulation on the SAW propagation. The high electromechanical coupling coefficients of the GaN/AlGaN substrate ($K_{eff}^2 = 0.001-0.002$), in combination with the low acoustic loss

and SAW high velocity, enable their use in high-frequency and diverse low-loss RF applications. Therefore, the GaN/AlGaIn-based SAW resonators operating up to the 10 GHz range can be designed and integrated with any wireless remote sensing applications.

[0056] Thus, using the GaN/AlGaIn heterostructure as the piezoelectric substrate for the SAW sensors will result in a considerable improvement of the detection limit and in a high selectivity. This is a result of the 2DEG/2DHG's sensitivity to any proximal surface charge and a high mass sensitivity, as explained above. Thus, the GaN/AlGaIn heterostructures and Schottky diodes can be integrated with a SAW sensor to create a rather unique resonant SAW tuning device with low acoustic loss, low loss RF performance and high frequency. The 2DEG/2DHG in a GaN/AlGaIn structure and in a SAW propagation path interacts with the lateral electric field, resulting in ohmic loss, which attenuates and slows the SAW. This mechanism can be used to tune the SAW propagation velocity.

[0057] However, to combine the 2DEG/2DHG with the SAW achieving a maximal sensory effectiveness, some physical aspects must be taken into account. The actual functional combination of the 2DEG/2DHG with the SAW requires complete or partial removal, depletion or appropriate patterning of the 2DEG/2DHG in the quantum-well channel in the acoustic wave propagation region. The high charge conductivity in the conducting 2DEG/2DHG channel can screen the electric field and reduce the acoustoelectric transductions in the IDTs.

[0058] The metallic IDTs introduce inherent mass loading effects and triple-transit-interference (TTI), reducing the signal-to-noise ratio. In conventional SAW sensors, the average SAW propagation velocity under the metallic IDTs will be reduced from the free-surface value and will result in a reduction of its centre frequency with an increased amplitude and phase rippling across the bandpass due to signal reflection from the metallic IDTs.

[0059] The aforementioned problems can be overcome by using the IDT fingers based on the PC-HEMT-like structures whilst also increasing the sensor sensitivity. In that case, the RF characteristics of the SAW device with planar 2DEG/2DHG IDTs are nearly equal to those using metallic IDTs with a Schottky contact. Moreover, the resulting mass-loading effects and the TTI are suppressed when using the 2DEG/2DHG-based transducers instead of the metallic IDTs. Also, the detection area of the SAW sensor or resonator can be right on top of the planar 2DEG/2DHG IDTs rather than in a separate SAW propagation area in between the IDTs. **Fig. 8** schematically shows a sensor with such 2DEG/2DHG IDTs on top of a GaN/AlGaIn heterostructure.

[0060] In general, when the metallic IDTs are placed on a semiconductor material, the Schottky contact is formed between the metal and the semiconductor, as explained above (regarding non-ohmic contacts). Considering the charge sensitivity mechanism in the 2DEG/2DHG-based SAW devices, other charge sensitive 2DEG/2DHG areas can be added that operate in either the resonant centre frequency or in other resonant modes. These additional patterned 2DEG/2DHG areas will further enhance the resonant changes in the main SAW sensor through their charge gating. By studying the different signal shapes for different

resonant modes, a selective sensing can be introduced.

[0061] Besides the charge-sensitive 2DEG/2DHG IDTs, other functional elements based on the 2DEG/2DHG conducting channel, such as a 2DEG/2DHG-Schottky diode and a 2DEG/2DHG-planar non-symmetrical diode, nanowires and high electron mobility transistors can be placed between and connected with input and output IDTs operating in a resonant filter mode, as shown in **Fig. 8**. The electrical characteristics of such functional elements are modulated due to acoustoelectric transduction, which is time correlated (synchronized with IDTs). This results in a minimal electric loss and a specified signal shape for the SAW resonance. Through the electrostatic field gating, for example by redox processes occurring on the surface, this resonant SAW filter mode is easily affected (frequency, amplitude).

[0062] Thus, due to its piezoelectric nature, the GaN/AlGaN heterojunction structures can be used as SAW sensors on the free standing GaN/AlGaN membrane. It is known, that the SAW sensors are very sensitive to surface charges in the SAW propagation path between emitter and receiver finger-electrodes or IDTs. In addition, the SAW sensors have a very high Q-factor at the resonant frequency. Moreover, the SAW sensors can be easily powered by an RF field with the corresponding frequency having an appropriate meander-based antenna. The SAW sensor offers the intrinsic RFID integration by using the orthogonal frequency coding. On the other hand, the 2DEG/2DHG-based sensors increase the evanescent near-field acoustoelectric effect through the 2DEG/2DHG-density charge-responsivity following by drastic increase of sensitivity to proximal electrical charges.

[0063] The functional basic topology of the sensor of an embodiment is schematically shown in **Figs. 9a** and **9b**. The aim of the 2DEG/2DHG-SAW sensor topology is to achieve the largest possible effect of the SAW-transducer S₂₁-transfer parameter without sacrificing the sensor stability. Lines (100) in **Figs. 9a** and **9b** are assigned to the metal IDT structures, band (102) stands for a PC-HEMT-like structure, which is actually a 2DEG/2DHG structure recessed to the thickness of 5-9 nm to achieve the pseudo-conducting effect, and area (103) shows the GaN/AlGaN piezoelectric substrate growing optionally on free-standing membranes (101).

[0064] Thus, in one aspect, the SAW RFID sensor chip of the present application comprises:

a piezoelectric substrate (103) optionally growing on free standing membranes (101), said substrate comprising a piezoelectric layer and a multilayer heterojunction structure, said structure being made of III-V single-crystalline or polycrystalline semiconductor materials, deposited on said piezoelectric layer and comprising at least one buffer layer and at least one barrier layer, said layers being stacked alternately;

at least one pair of metal interdigitated transducers (IDT) (100) mounted on said piezoelectric substrate (103), for receiving a radio frequency (RF) input signal, transducing said input signal into a surface acoustic wave (SAW), propagating said surface acoustic wave along a surface of said piezoelectric substrate (103) and transducing said propagated surface acoustic wave into an output RF signal;

at least one PC-HEMT-like structure (102) deposited on said piezoelectric substrate (103) for forming the pseudo-conducting 2DEG or 2DHG channel in said heterojunction structure at the interface between said buffer layer and said barrier layer; and

electrical metallizations (not shown in the figure) capacitively-coupled to said IDTs (100) and to said PC-HEMT-like structures (102) for inducing displacement currents, thereby creating non-ohmic source and drain contacts, for connecting said sensor chip to an electric circuit.

[0065] Using this configuration with the free-standing membranes makes it possible to increase selectivity of the sensor via adding mechanical stress (mass loading effect) as an additional parameter of the sensor. The very flexible free-standing substrate columns-like membranes (101) can be made of the same material as the piezoelectric substrate layer (103) in all configurations of the sensor. In a particular embodiment, the free-standing membranes (101) are grown, for example, from sapphire, silicon, silicon carbide, gallium nitride or aluminium nitride, preferably gallium nitride (GaN), having thickness of 0.5-2 μm . As an example, the free-standing substrate membranes show high sensitivity to any tensile/compressive/mechanical stress changes on the surface of the multilayer heterojunction structure. This results in a mass loading effect, which will be discussed below.

[0066] In general, mechanical sensors, much like pressure sensors, are based on the measurement of the externally induced strain in the heterostructures. The pyroelectric properties of group-III-nitrides, such as gallium nitride (GaN), allow two mechanisms for strain transduction: piezoelectric and piezoresistive. The direct piezoelectric effect is used for dynamical pressure sensing. For measurements of static pressure, such sensors are not suitable due to some leakage of electric charges under the constant conditions. For static operation, the piezoresistive transduction is more preferable.

[0067] Piezoresistive sensors using wide band gap materials have been previously employed using hexagonal silicon carbide bulk materials for high temperature operation. A piezoresistivity of GaN and AlGaN structures is comparable to silicon carbide. However, the piezoresistivity can be further amplified by any HEMT structure, as taught by Eickhoff et al (2001) in "Piezoresistivity of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers and $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures", Journal of Applied Physics, 2001, 90(7), 3383-3386. For piezoresistive strain sensing at relatively lower pressures (or pressure differences), diaphragm or membranes should be used, where the external pressure is transferred into a changed internal strain caused by bending, as shown in **Fig. 9c**. The resulting change in polarization alters the 2DEG/2DHG channel current which is measured.

[0068] Eickhoff et al (2001) conducted the first experiments on AlGaN/GaN heterostructures where the 2DEG channel confined between the upper GaN and AlGaN barrier layer and demonstrated the linear dependence of the 2DEG channel resistivity on the applied strain. Moreover a direct comparison to cubic SiC and a single AlGaN layer clearly demonstrated the superior piezoresistive properties of the latter. From these results, it is clear that the interaction

of piezoelectric and piezoresistive properties improves the sensitivity of pressure sensors by using GaN/AlGaN heterostructures confined with the 2DEG channel.

[0069] The sensor configuration schematically shown in **Figs. 9a** and **9b** involves piezoelectrically coupled, charge and mass sensitive, free-standing GaN membranes, which are prepared, for example, according to U.S. Patent No. 8,313,968, and offer an elegant and effective solution to achieve both downscaling and an integrated all-electrical low-power sensing-actuation. As mentioned above, GaN exhibits both, piezo- and pyro-electrical properties, which can be functionally combined. Whereas the piezoelectricity enables realisation of an integrated coupling mechanism, the 2DEG/2DHG additionally delivers a pronounced sensitivity to mechanical stress and charge, which allows the sensor to use the pyroelectric effects. The dynamic change in 2DEG/2DHG conductivity is also caused by a change in piezoelectric polarisation.

[0070] **Figs. 10a** and **10b** show another configuration, which is very similar to the configuration shown in **Fig. 9a-9b** discussed above. However, here a resonating piezoelectric ultrathin film (104) is introduced on top of the substrate (103). A bulk wave propagating inside the piezoelectric ultrathin film (104) is generated by putting it between two electrodes and applying a high frequency signal. The wave resonates at a particular frequency according to the thickness of the ultrathin film. Such resonator is called a Film Bulk Acoustic Resonator (FBAR), and it is combined in the sensor of an embodiment with the PC-HEMT-like structure (102) for achieving maximum sensitivity. The FBAR traditionally uses aluminium nitride (AlN) as its piezoelectric material, however other group-III-nitrides can be a possible alternative.

[0071] In general, the structures of FBARs are made by forming cavities with a dry-etching machine called a "Deep-RIE" from the reverse side of the substrate or by using a sacrifice layer, forming the sacrifice layer under the lower electrode, a piezoelectric thin film and upper electrode, then removing the layer to make a space beneath the lower electrode.

[0072] The low-side and upper-side electrodes shown in **Fig. 10b** are designed with so-called "leaky waves" having acoustic wave velocities of around 4000 m/s. "Leaky waves" can be defined as propagating waves that concentrate most of the energy close to the surface of the substrate, but have some radiation of bulk waves into the substrate while propagating. The piezoelectric substrate used for forming leaky waves is normally made of a LiTaO₃ single crystal having X, Y and Z axes and a cut plane. The X axis of the crystal is oriented in a direction of the SAW propagation, while the cut plane of the crystal is rotated around the X axis at a certain angle of rotation with respect to the Y axis towards the Z axis. This angle normally ranges between 40° and 42°. That is why the substrate is commercially named "42° Y-X LiTaO₃". The IDTs (100) are formed on the substrate and aligned in a row in the direction of the SAW propagation, as shown in **Fig. 10a**.

[0073] Each IDT has a pair of mutually opposed primary electrode fingers (shown as lines (100) in **Figs. 10** and **11**) and secondary electrode fingers (shown in **Fig. 9**) and includes at least one front transducer, one middle transducer and one rear transducer, which are aligned

in the row in the direction of the SAW propagation, as shown in **Fig. 10a**.

[0074] **Fig. 11** shows the photolithographic layout masks of the 2DEG-based SAW resonator using the standard configuration with two symmetrical IDT structures (fingers). The IDT fingers are preferably made of Cr10/60Au metal alloys and have a preferable width of 200, 300, 400, 500 or 700 nm. They are fabricated in one e-beam step as a lift-off bi-layer resist system stack or a negative resist and ion milling. The 2DEG/2DHG is not structured in that case and interacts with the surrounding medium. The area (601) in the middle represents the primary IDT fingers on a free-standing area, where the (silicone) substrate will be removed by the deep reactive-ion etching (DRIE) process, as mentioned above.

[0075] **Fig. 12** shows the SEM images of the SAW resonator of an embodiment as shown in **Figs. 9-11**. This SAW resonator is fabricated via the lift-off/or ion-milling patterning technique. **Fig. 13** shows the microscope images of these SAW resonators on the free-standing GaN/AlGaN membranes having the unstructured 2DEG/2DHG area with the silicon substrate removed via the DRIE process. The SAW IDTs shown here have different IDT periods ranging from 200 nm to 700 nm and hence, reflect light differently. In general, leaky waves are frequently used in these kinds of substrates for their relatively large electromechanical coupling coefficient, which enables them to form a relatively wide passband required for transmitting and receiving mobile device signals. For example, in the present SAW resonator having a working frequency of 2 GHz, the wavelength λ is calculated from $\lambda \times 2 \times 10^9 = 4000 \text{ m/s}$, resulting in $\lambda = 2 \text{ }\mu\text{m}$. This calculated wavelength should be equal to the length twice as the electrode pitch for excitation, and assuming that the spaces between the electrodes are the same as the electrode width, the width of the electrode is estimated to be $0.5 \text{ }\mu\text{m}$. The actual spaces between the electrodes are about $0.7 \text{ }\mu\text{m}$ as seen in **Fig. 12**.

[0076] Thus, the IDT structures (100) receive the RF signal of about 0.5-2.5 GHz and exhibit the piezoelectric effect creating acoustic waves over the surface of the resonator. These surface acoustic waves propagate along the substrate with constructive interference from both input and output IDTs. As shown in **Figs. 9-10**, the PC-HEMT-like structure (102) is placed in the SAW bidirectional propagation path and also patterned in such a manner as to electrically shortcut the positive and negative electric charges from running the SAW and to thereby considerably change or minimize the amplitude of the signal which is received on both IDTs via the direct piezoelectric effect. The SAW itself is generated by zero-power meander antenna (not shown here) connected to both IDTs (100).

[0077] In the above sensor configuration of an embodiment, shown in **Figs. 9-10**, the piezoelectric substrate (103) comprises a suitable material for forming the barrier layer and is composed, for example, of sapphire, silicon, silicon carbide, gallium nitride or aluminium nitride. The heterojunction structure made of GaN/AlGaN is deposited on this piezoelectric substrate layer, for example, by a method of metalorganic chemical vapour deposition (MOCVD). The PC-HEMT-like structure (102) is created in a close proximity to the interface between the GaN buffer layer and the AlGaN barrier layer. The specific thickness of 5-9 nm of the AlGaN barrier layer is achieved by either dry etching the semiconductor material of the

layer, i.e. recessing layer in the open gate area with the etching rate of 1 nm per 1-2 min in a controllable process, or coating the AlGaIn buffer layer with an ultrathin layer of the AlGaIn semiconductor material. In order to increase the charge sensitivity of the sensor, the surface of the recessed ultrathin AlGaIn layer is post-treated with the plasma (chloride) epi-etch process. Consequently, the natively passivated surface is activated by the plasma etch to create an uncompensated (i.e. ionised) surface energy bonds or states, which are neutralized after the MOCVD growing.

[0078] The barrier layer then may be either recessed or grown as a thin layer to get the pseudo-conducting 2DEG/2DHG channel, which is formed at the interface between the buffer GaN layer and the barrier AlGaIn layer, as described above in detail. The recessed GaN/AlGaIn structure is actually a PC-HEMT-like structure (because of its specific thickness) resulting in a pseudo-conducting current in the 2DEG/2DHG channel. As explained above, this channel formed at the interface between the buffer GaN layer and the barrier AlGaIn layer serves as a main sensitive element of the sensor reacting to a surface charge and potential. The formed 2DEG/2DHG channel is configured to interact with very small variations in surface or proximal charge or changes of electrical field as a result of the propagating surface acoustic waves creating a piezoelectric effect, and thereby, interacting with the donor-like surface trap states of the AlGaIn barrier layer.

[0079] **Fig. 14** schematically shows a method for non-destructive detection of the pipe content (for example, oil, gas or sand) and monitoring the structural pipe material health using an ultrasensitive microphone (200) or microphones array of an embodiment. The microphone (200) is actually a 2DEG-FBAR-SAW sensor (enlarged in the layout) of the embodiment. The method comprises the following steps:

1. 1) Placing the ultrasound emitter actuator (201) directly on the pipe;
2. 2) Placing the microphones (200) either in a circle around the the ultrasound emitter actuator (201) or laterally shifted along the pipe (as in **Fig. 14**); and
3. 3) Detection or monitoring of the reflected ultrasound wave front (202) either with a single microphone (200) or with the microphones array (as in **Fig. 14**).

[0080] The microphones array creates a passive phase array configuration allowing considerably more accurate and selective detection of the chemical content in the pipe. A microscope image of the ultrasensitive microphone of the present application built by the present inventors is shown in **Fig. 15a**. It is actually a SAW resonator chip, as described above, incorporating the PC-HEMT-like structure for increasing sensitivity of the sensor. The SAW itself is generated by a zero-power meander antenna shown in **Fig. 15b**. The sensor with the meander antenna has dimensions of 5-30 mm (length) × 1-5 mm (width), while the SAW resonator chip is about 2 mm². The SAW resonator chip has a direct mechanical contact with a material to be sensed, such as an outer wall of the pipe. The detection and monitoring of the pipe content, which is usually water, oil, sand or gas, is based on the ultrasound wave front

reflection from the metal wall or content of the pipe at the interface between the wall and the content.

[0081] Amplitude of the reflected ultrasound signal is very low due to a very high initial ultrasound wave coupling and multiple secondary ultrasound wave reflections lose. In general, the amplitude, shape, phase and Doppler shift of the ultrasound wave front reflected at the interface between the pipe wall and the pipe content is mostly depending on density, pressure, composition and speed of the content flow inside the pipe. A single microphone of the present application is extremely sensitive to the ultrasound wave energy interacting with a highly pyroelectric GaN/AlGa_N heterojunction. The highest sensitivity of the microphone can be reached only at the resonant frequencies of this microphone. The higher the resonance frequency, the lower is the detection limit and higher is sensitivity. In order to achieve the resonant frequencies, the present inventors proposed to use the hybrid FBAR-SAW on the free-standing GaN/AlGa_N membranes transducing the SAW waves, as described above, and having the first harmonic resonant frequency with high amplitude compared to non-free standing structures. These new prototype FBAR-SAW resonators of **Fig. 13** designed and built by the inventors are shown in **Fig. 16** together with the schematic drawing of the FBAR-SAW resonator based on the free-standing membranes placed in contact with the pipe being sensed.

[0082] Each ultrasensitive microphone (200) shown in **Fig. 14** may be RFID-coded, have a zero-power NFC capability and further be equipped with a bidirectional receiver-emitter antenna structure. It is also possible to couple all the microphones to a single meander antenna and separate the mixed RFID-patterned signals by orthogonal frequency coded (OFC) from individual microphones by an algorithm, which will be disclosed elsewhere. This will allow building a zero-power SAW-sensor array without batteries and cable connections, thereby drastically reducing the sensor cost. Each SAW microphone can be further phase controlled and can detect the smallest phase change of the SAW. By operating the sensors in a phased array configuration, it will be possible to measure, for example, flow rate, liquid laminarity and gas fractions.

[0083] **Fig. 17** schematically shows an ultrasensitive microphone of an embodiment, for material and structure sensing, with a remote readout, comprising the following components:

- the SAW sensor chip (120) of the application connected via contacts (123) to an electric circuit (122);
- one or two out-input SAW-RFID zero-power fractal antennas (130), each connected to said contacts (123) via the electric circuit (122) for receiving or transmitting a signal;
- an output-input separation by delay line SAW transducer (118);
- an integrated circuit (112) for storing and processing said signal, and for modulating and demodulating a radio-frequency (RF) signals, said circuit comprising:

1. a) a voltage source (114) supplying electric current to said SAW sensor chip (120) and to

- said one or two antennas (130);
2. b) an integrated or CMOS current amplifier (115) for amplification of an electric current obtained from said SAW sensor chip (120);
 3. c) an analogue-to-digital converter (ADC) with wireless input/output modules (116) connected to said current amplifier (115) for wireless outputting the converted signal to a user interface or external memory;
 4. d) a microcontroller unit (MCU) (113) for processing and converting the received signal into data readable in said user interface or external memory; and
 5. e) a wireless connection module (117) for wireless connection of said sensor to said user interface or external memory.

[0084] The voltage source (114) can be any suitable and commercially available battery of the Li-ion type, any energy harvester with AC-DC or DC-DC converters or photovoltaic element. The ADC card (116) is any suitable analogue-to-digital converter data logger card that can be purchased, for example, from National Instruments® or LabJack®. The current amplifier (115) is connected in-line and can be any commercially available femtoampere amplifier, for example SRS® SR570, DLPVA-100-F-S, FEMTO® current amplifier DDPCA-300 or Texas Instruments® INA826EVM. Optionally, a current amplifier can be operated directly with current flowing via the 2DEG/2DHG channel of the 2DEG/2DHG structures into the amplifier with small input resistance of $1\text{M}\Omega$ at gain higher than 10^4 and only 1Ω at gains lower than 200. This setup may directly amplify the electric current modulation in the 2DEG/2DHG channel originated from an external body charges. All readout components are battery powered to avoid ground loop parasitic current.

[0085] In a specific embodiment, the wireless connection module (117) can be a short-range Bluetooth® or NFC providing wireless communication between the wearable device or gadget and a smartphone for up to 20 m. If this module is Wi-Fi, the connection can be established with a network for up to 200 nm, while GSM allows the worldwide communication to a cloud. The external memory may be a mobile device (such as a smartphone), desktop computer, server, remote storage, internet storage or material diagnostics cloud.

[0086] As shown in the present application, the sensors of the embodiments are used as ultrasensitive portable microphones for material and structure sensing. The portable sensor of an embodiment should have a very small power consumption saving the battery life for a prolong usage. In this case, the non-ohmic high-resistive contacts capacitively connecting the sensor to an electric circuit are preferable. In fact, the non-ohmic contacts are capable of limiting an electric current flowing through the 2DEG/2DHG conducting channel by having an electrical resistance 3-4 times higher than the electrical resistance of the 2DEG/2DHG-channel, thereby reducing electrical power consumption without sacrificing sensitivity and functionality of the sensor. Thus, the use of the non-ohmic contacts in the sensor of the embodiments is a hardware solution allowing minimising the power consumption of the device. In another embodiment, the power consumption of the device can be minimised using a software

algorithm managing the necessary recording time of the sensor and a battery saver mode, which limits the background data and switches the wireless connection only when it is needed.

[0087] As described above, the sensor of the present application can be realised in two configurations: with and without free-standing membranes. In the first configuration, the piezoelectric substrate is optionally placed on a GaN/AlGaN free-standing membrane resulting in a FBAR-SAW configuration, for achieving ultra-sensitivity. In another configuration, the sensor is based on a regular silicon piezoelectric substrate firmly connected to a structural material, such as metal pipe, being tested. In case of any stress or mechanical deformation of this structural material, the piezoelectric GaN/AlGaN stack will be also stressed or deformed, thereby changing the SAW propagation parameters. This is because of the piezoelectric polarization effect within the SAW structures resulting in change of the S21 transfer parameter on the IDT receiver.

[0088] Alternatively, the sensor of an embodiment, may be based on a piezoelectric electro-optical crystal transducer (EOC) combined with the PC-HEMT-like structure (recessed 2DEG/2DHG-based structure). The sensor based on the EOC piezoelectric substrate exhibits the highest coupling between electrical and mechanical energy compared to all other varieties of substrates. Additionally, such a substrate also has the advantages of having a high velocity-shift coefficient and a very high electromechanical coupling coefficient, K_2 , which yields a greater mass sensitivity in comparison with the same regular SAW device on any other piezoelectric substrates. The EOC may be any suitable electro-optical crystalline material such as LiNbCO_3 , which is brought into a physical contact with a single point on a user's body. The EOC is then illuminated with a polarised light.

[0089] In case of the LiNbO_3 crystalline material, the wavelength of the polarised light is about 400-600 nm. Modulated light from the light source illuminates the EOC, and then falls on the 2DEG/2DHG-based structure. The 2DEG/2DHG-based structure is ultrasensitive to an incident light creating the p-n-pairs in the AlGaN barrier layer, thereby strongly affecting the 2DEG/2DHG-channel conductivity. In general, irradiation of the 2DEG/2DHG-based structure with light switches the 2DEG/2DHG-channel from normally-off to a pseudo-conducting or normally-on state. Therefore, by contact with a body, the EOC is capable of changing its light absorbance strongly affecting the electrical current flow in the 2DEG/2DHG channel, thereby resolving any smallest light intensity changes coming from the EOC transducer. Depending on the excitation light wavelength, the position of the sensor relative to the incident light beam can be changed. For instance, in case of IR light (700-1500 nm), the sensor should be placed perpendicularly to the light beam for achieving the highest sensitivity. The parasitic charging of the EOC is compensated via the electrodes attached to the crystal. Additionally a variety of light filters in front of the sensor can be utilised.

[0090] In still another embodiment, **Fig. 18** schematically shows an optoelectronic sensing device of an embodiment, for material and structure sensing, with a remote readout comprising the following components:

- the SAW sensor chip (120) of the application connected to an electric circuit;
- a modulated light source (125), such as a surface-mounted-device light-emitting diode (SMD LED) or UV-VIS-IR laser diode, for irradiating the AlGaIn barrier layer surface of the pseudo-conducting 2DEG/2DHG structure (126) on the sensor chip;
- optocoupler switches (124) for coupling said modulated light source (125) with said pseudo-conducting 2DEG/2DHG structure (126) on the sensor chip;
- a voltage source (104) connected to said electrical circuit for supplying electric current to said SAW sensor chip (120);
- a lock-in amplifier (119) connected to said voltage source (104) for amplification of a signal with a known carrier wave obtained from said SAW sensor chip and increasing the signal-to-noise ratio; and
- an analogue-to-digital converter (ADC) with in-built digital input/output card (106) connected to said lock-in amplifier (119) for outputting the converted signal to a user interface or external memory.

[0091] Thus, the use of the SAW-EOC configuration makes it possible to drastically increase the sensitivity of the sensor to an electrical charge, to discharge the EOC via the SAW-based charge transport along the crystal surface, to efficiently modulate polarised light from the light source and to control the SAW delay line effect with the phase velocity signal. The optocoupler switches (124) couples the 2DEG/2DHG-based structure (126) with the SAW-EOC such that the initial SAW actuation signals at the IDT emitter (left) electrodes are synchronised with the modulated light source (125) and with the V_{DS} at the pseudo-conducting 2DEG/2DHG-based structure. A signal at the IDT receiver (right) electrodes is coupled back to the V_{DS} via the opto-coupler (124), which is brought into a resonance with initial signals and with the light source (125) modulation. Due to a physical galvanic connection of the SAW-EOC with the body single point by spatially patterned electrodes, the EOC changes its light absorption and modulation properties. This strongly affects the resonant mode of the five initial signal sources (V_{DS} , emitter IDT, light source, receiver IDT and SAW-modulated light source). Thus, because of the light source-based interaction, the resonant system becomes very stable and also very sensitive to external charges.

[0092] Fig. 19 shows the experimental S21-transfer parameter measured with the ultrasensitive microphone of the embodiments. In some embodiments, a method for material and structure sensing comprises the following steps:

1. 1) Applying the sensing device of the embodiments to a material or structure to be sensed;
2. 2) Recording signals received from the material or structure in a form of a S21-transfer parameter dynamics of the device over time (defined as S21-transfer dynamics) with

said device;

3. 3) Transmitting the recorded signals from said device to the external memory for further processing; and
4. 4) Converting the transmitted signals to digital signals and processing the digital signals in the external memory, correlating said S21-transfer dynamics with pre-calibrated material or structure waveforms stored in the external memory, and extracting the material or structure information from said waveforms in a form of readable data.

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AKUSTISK OVERFLADEBØLGE-RFID-SENSOR TIL MATERIALE- OG STRUKTURREGISTRERING

PATENTKRAV

1. Akustisk overfladebølge-(SAW)-radiofrekvensidentifikations-(RFID)-sensorchip, der omfatter:
 - (a) et piezoelektrisk substrat (103), hvilket substrat omfatter:
et piezoelektrisk lag og
en flerlagsheteroovergangsstruktur, idet strukturen er fremstillet af III-V enkeltkrystallinske eller polykrystallinske halvlederlag, som er afsat på det piezoelektriske lag og omfatter mindst ét bufferlag og mindst ét barrierelag, idet lagene er stablet skiftevis;
 - (b) mindst ét par af interdigiterede transducere (IDT) (100) af metal, der er monteret på det piezoelektriske substrat (103), til modtagelse af et radiofrekvens-(RF)-inputsignal, transduktion af inputsignalet til en akustisk overfladebølge (SAW), propagering af den akustiske overfladebølge langs en overflade af det piezoelektriske substrat og transduktion af den propagerede akustiske overfladebølge til et output-RF-signal;
 - (c) mindst én pseudoledende todimensional elektrongas-(2DEG)- eller todimensional hulgas-(2DHG)-struktur (102), som er afsat på det piezoelektriske substrat (103) til dannelse af en pseudoledende 2DEG- eller 2DHG-kanal i heteroovergangsstrukturen ved grænsefladen mellem bufferlaget og barrierelaget; og
 - (d) elektriske metalliseringer, der er kapacitivt koblet til IDT'erne (100) og til de pseudoledende 2DEG- eller 2DHG-strukturer (102) til inducering af forskydningsstrømme, hvorved der dannes ikke-ohmske source- og drain-kontakter med henblik på at forbinde sensorchippen med et elektrisk kredsløb;

kendetegnet ved, at:

- (i) de III-V enkeltkrystallinske eller polykrystallinske halvledermaterialer er GaN/AlGaN; og
- (ii) den pseudoledende 2DEG- eller 2DHG-struktur (102) er en halvledende struktur, der er dannet på det piezoelektriske substrat (103) ved forsækning eller dyrkning af et øverste lag af flerlagsheteroovergangsstrukturen til en tykkelse på 5-9 nm, idet en overfladeruhed for det forsænkede eller dyrkede øverste lag er 0,2 nm eller derunder, hvorved den pseudoledende 2DEG- eller 2DHG-kanal, som er i stand til at lede elektrisk strøm i strømområdet mellem normalt åbne og normalt lukkede driftsmodi for kanalen, dannes.

2. SAW-RFID-sensorchip ifølge krav 1, hvor:

- (A) flerlagsheteroovergangsstrukturen indeholder ét GaN-bufferlag nederst og ét AlGaN-barrierelag øverst, hvor AlGaN-barrierelaget har (i) en tykkelse på 5-9 nanometer (nm), svarende til det pseudoledende strømområde mellem den normalt åbne og normalt lukkede driftsmodus for den dannede 2DEG-kanal, og (ii) en overfladeruhed på 0,2 nm eller derunder; eller
 - (B) flerlagsheteroovergangsstrukturen er sandwichlignende og indeholder ét GaN-bufferlag øverst, ét GaN-bufferlag nederst og ét AlGaN-barrierelag derimellem, hvor den 2DEG-ledende kanal er dannet i det øverste GaN-bufferlag over AlGaN-barrierelaget, tæt på grænsefladen mellem det øverste GaN-bufferlag og AlGaN-barrierelaget, hvilket resulterer i en N-fladepolaritet for strukturen, hvor det øverste GaN-bufferlag har (i) en tykkelse på 5-9 nanometer (nm), svarende til det pseudoledende strømområde mellem den normalt åbne og normalt lukkede driftsmodus for den dannede 2DEG-kanal, og (ii) en overfladeruhed på 0,2 nm eller derunder; eller
 - (C) flerlagsheteroovergangsstrukturen er sandwichlignende og indeholder ét GaN-bufferlag øverst, ét GaN-bufferlag nederst og et AlGaN-barrierelag derimellem, hvor den 2DHG-ledende kanal er dannet i det øverste GaN-bufferlag over AlGaN-barrierelaget, tæt på grænsefladen mellem det øverste GaN-bufferlag og AlGaN-barrierelaget, hvilket resulterer i en Ga-fladepolaritet for strukturen, hvor det øverste GaN-bufferlag har (i) en tykkelse på 5-9 nanometer (nm), hvilket svarer til det pseudoledende strømområde mellem den normalt åbne og normalt lukkede driftsmodus for den dannede 2DHG-kanal, og (ii) en overfladeruhed på 0,2 nm eller derunder.
- 3.** SAW-RFID-sensorchip ifølge krav 1 eller 2, hvor tykkelsen på det øverste lag af flerlagsheteroovergangsstrukturen er 6-7 nm, fortrinsvis 6,2-6,4 nm.
- 4.** SAW-RFID-sensorchip ifølge et hvilket som helst af kravene 1-3, hvor det øverste lag af flerlagsheteroovergangsstrukturen har en overfladeruhed på ca. 0,1 nm eller derunder, fortrinsvis ca. 0,05 nm eller derunder.
- 5.** SAW-RFID-sensorchip ifølge krav 1, hvor det piezoelektriske substrat er placeret på en fritstående membran (101).

6. SAW-RFID-sensorchip ifølge krav 5, hvor den fritstående membran (101) er fremstillet af safir, silicium, siliciumcarbid, galliumnitrid eller aluminiumnitrid.
7. SAW-RFID-sensorchip ifølge krav 1, hvor det piezoelektriske lag er fremstillet af zinkoxid, safir, aluminiumnitrid, lithiumtantalat, lithiumniobat, kaliumniobat, lanthangalliumsilicat, silicium, siliciumcarbid eller kvarts.
8. SAW-RFID-sensorchip ifølge et hvilket som helst af kravene 1-7, hvor metal-IDT'erne (100) er i stand til at modtage RF-signalet på ca. 0,5-2,5 GHz og udviser den piezoelektriske virkning ved at danne akustiske bølger over det piezoelektriske substrats (103) overflade.
9. SAW-RFID-sensorchip ifølge et hvilket som helst af kravene 1-8, der endvidere omfatter en excitationslyskilde til bestråling af det piezoelektriske substrat, hvorved der induceres en elektrisk strøm i 2DEG- eller 2DHG-kanalen.
10. SAW-RFID-sensorchip ifølge krav 9, hvor excitationslyskilden er en lysemitterende diode på en overflademonteret anordning (SMD FED) eller en UV-VIS-IR-laserdiode.

11. Sensoranordning med en fjernudlæsning til materiale- og strukturregistrering, hvilken sensoranordning omfatter:

SAW-RFID-sensorchippen ifølge et hvilket som helst af kravene 1-8, der er indsat i en sensoranordningsramme og forbundet med et elektrisk kredsløb (122);
 mindst én output-input-SAW-RFID-fraktalantenne (130), der er forbundet med det elektriske kredsløb (122), til modtagelse eller overførsel af et signal;
 en output-input-forsinkelseslinjeseparerings-SAW-transducer (118); og
 et integreret fjernkredsløb (112) til lagring og behandling af signalet og til modulering og demodulering af et radiofrekvens-(RF)-signal, hvilket integreret fjernkredsløb omfatter:

- a) en spændingskilde (114), der tilfører elektrisk strøm til SAW-RFID-sensorchippen og til output-input-SAW-RFID-fraktalantennen(-erne) (130);
- b) en integreret strømforstærker eller CMOS-strømforstærker (115) til forstærkning af en elektrisk strøm, som er opnået fra SAW-RFID-sensorchippen;
- c) en analog-digital-konverter med trådløse input-/outputmoduler (116), der er forbundet med strømforstærkeren (115), til trådløs generering af det omdannede

- signal til en brugergrænseflade eller ekstern hukommelse;
- d) en mikrocontrollerenhed (MCU) (113) til behandling og omdannelse af det modtagne signal til data, som er læsbare i brugergrænsefladen eller den eksterne hukommelse; og
- e) et trådløst forbindelsesmodul (117) med henblik på trådløst at forbinde sensoranordningen med brugergrænsefladen eller den eksterne hukommelse.

12. Sensoranordning med en fjernudlæsning til materiale- og struktureregistrering, hvilken sensoranordning omfatter:

SAW-RFID-sensorchippen ifølge kravene 9 eller 10, der er indsat i en sensoranordningsramme og forbundet med et elektrisk kredsløb;

en moduleret lyskilde (125) til bestråling af overfladen af de pseudoledende 2DEG- eller 2DHG-strukturer (126) af SAW-RFID-sensorchippen;

optokobleromskiftere (124) til kobling af den modulerede lyskilde (125) med de pseudoledende 2DEG- eller 2DHG-strukturer (126) af SAW-RFID-sensorchippen; en spændingskilde (104), der er forbundet med det elektriske kredsløb, til tilførsel af elektrisk strøm til SAW-RFID-sensorchippen;

en lock-in-forstærker (119), der er forbundet med spændingskilden (104), til forstærkning af et signal med en kendt bærerbølge, som er opnået fra SAW-RFID-sensorchippen, og til forbedring af signal-støj-forholdet; og

en analog-digital-konverter (ADC) med indbygget digitalt indgangs-/udgangskort (106), der er forbundet med lock-in-forstærkeren (119), til generering af det omdannede signal til en brugergrænseflade eller en ekstern hukommelse.

13. Sensoranordning ifølge krav 11 eller 12, hvor (i) den eksterne hukommelse er en mobil enhed, en desktop-computer, en server, et fjernlager, et internetdatalager eller en materialediagnose-cloud; eller (ii) spændingskilden (104) er et batteri af Li-ion-typen eller en energihøster med AC-DC- eller DC-DC-omformere; eller (iii) det trådløse forbindelsesmodul (117) er et kortrækkende Bluetooth®- eller NFC-modul, som tilvejebringer trådløs kommunikation mellem sensoranordningen og brugergrænsefladen, den mobile anordning eller desktop-computeren; eller et Wi-Fi-modul, som tilvejebringer trådløs kommunikation mellem sensoranordningen og brugergrænsefladen, en mobil anordning, desktop-computer eller server; eller et GSM-modul, som tilvejebringer en global trådløs kommunikation mellem sensoranordningen og en server, et fjerndatalager, et internetdatalager eller en

materialediagnose-cloud.

14. Sensoranordning ifølge et hvilket som helst af kravene 11-13, hvor anordningen er en ultrafølsom mikrofon.

15. Fremgangsmåde til materiale- og strukture registrering, hvilken fremgangsmåde omfatter:

- 1) anvendelse af sensoranordningen ifølge et hvilket som helst af kravene 11-14 på et materiale eller en struktur, der skal registreres;
- 2) registrering af signaler, der modtages fra materialet eller strukturen i form af en S21-overførselsparameterdynamik for anordningen over tid med anordningen;
- 3) overførsel af de registrerede signaler fra anordningen til den eksterne hukommelse med henblik på viderebehandling; og
- 4) omdannelse af de overførte signaler til digitale signaler, behandling af de digitale signaler i den eksterne hukommelse, korrelering af S21-overførselsdynamikken med prækalibrerede materiale- eller strukturbølgeformer, der er lagret i den eksterne hukommelse, og uddragning af materiale- eller strukturinformationerne af nævnte bølgeformer i form af læsbare data.

DRAWINGS

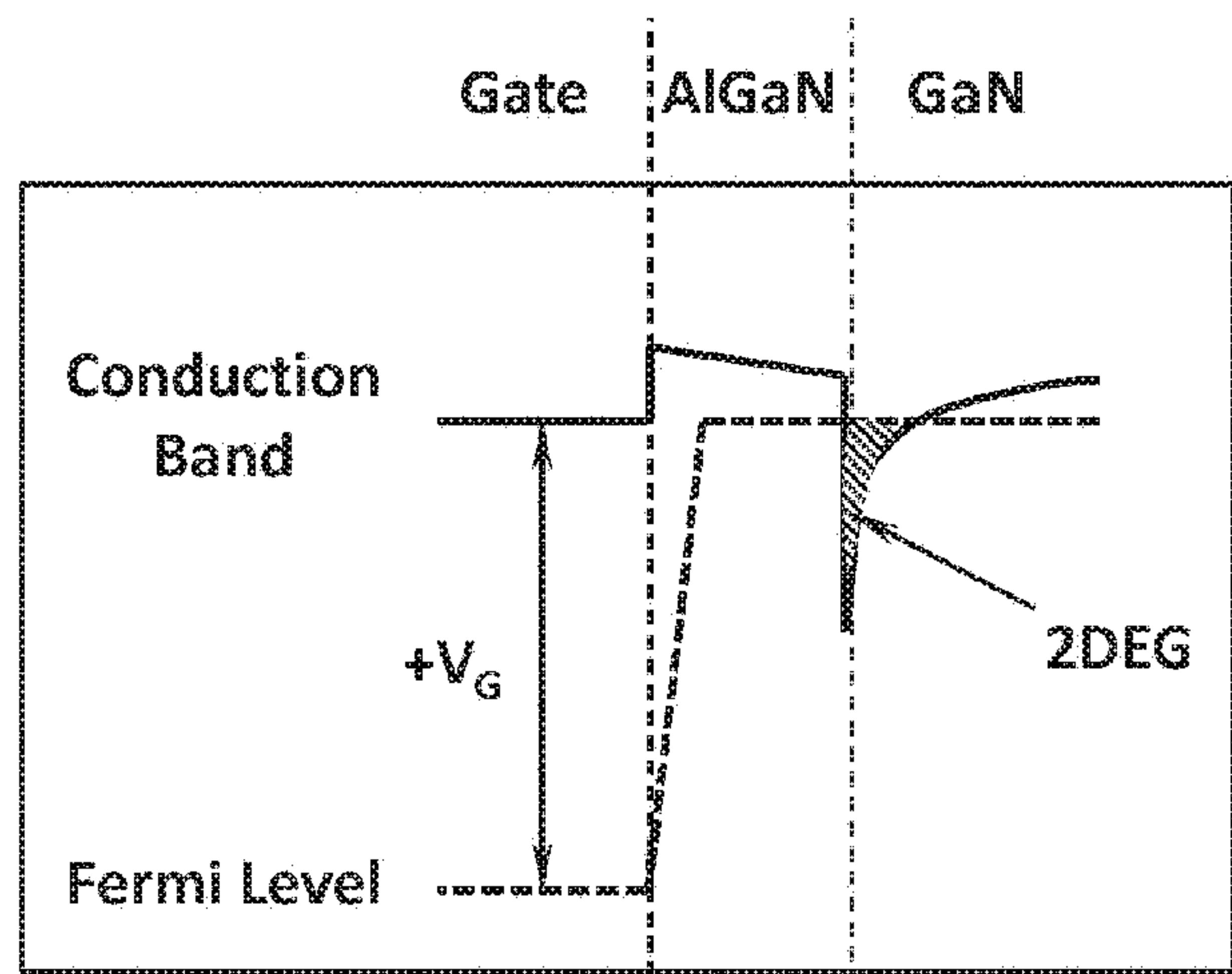


Fig. 1a

$V_G \gg V_T$

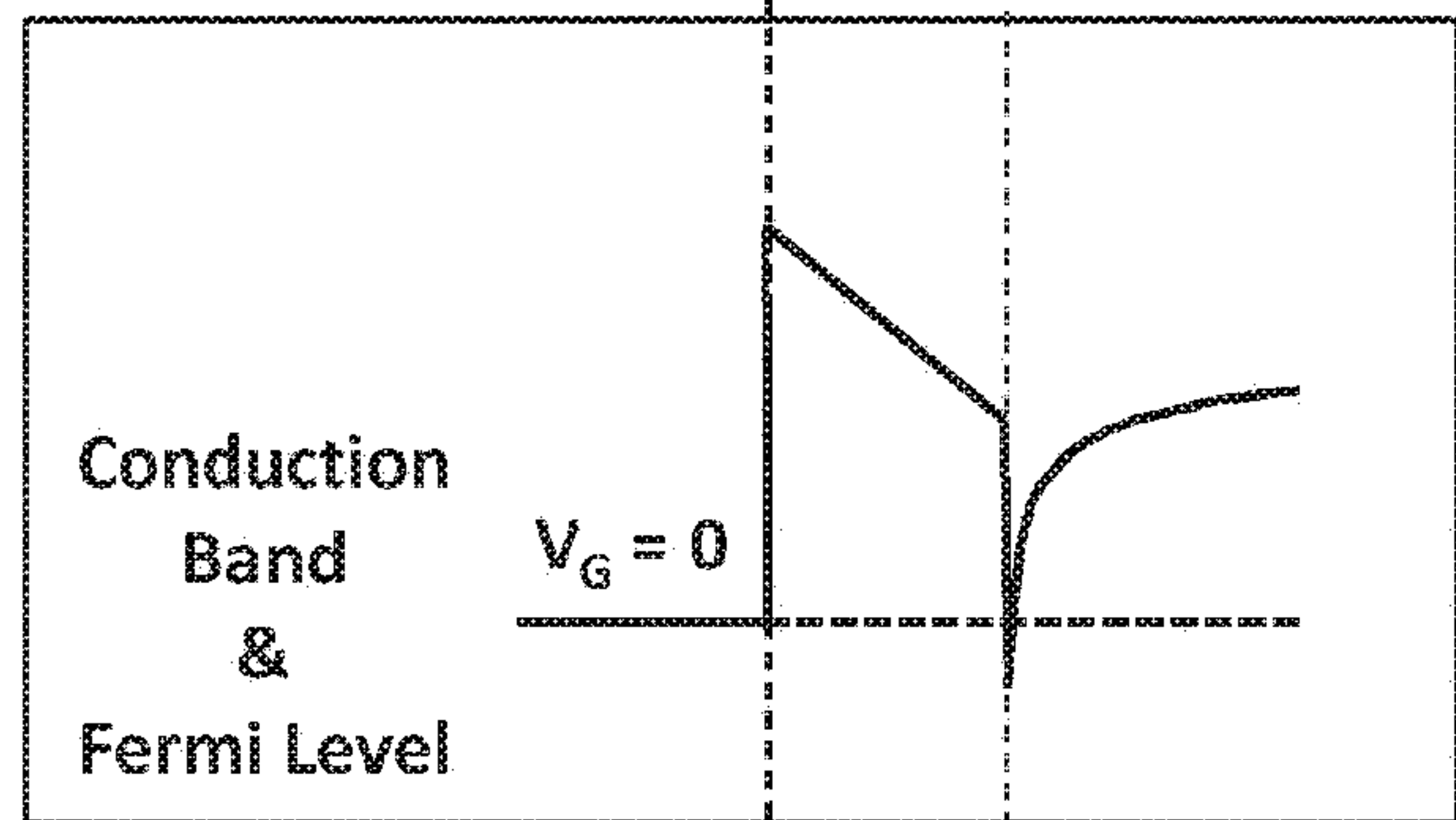


Fig. 1b

$V_G = 0$
 $V_G > V_T$

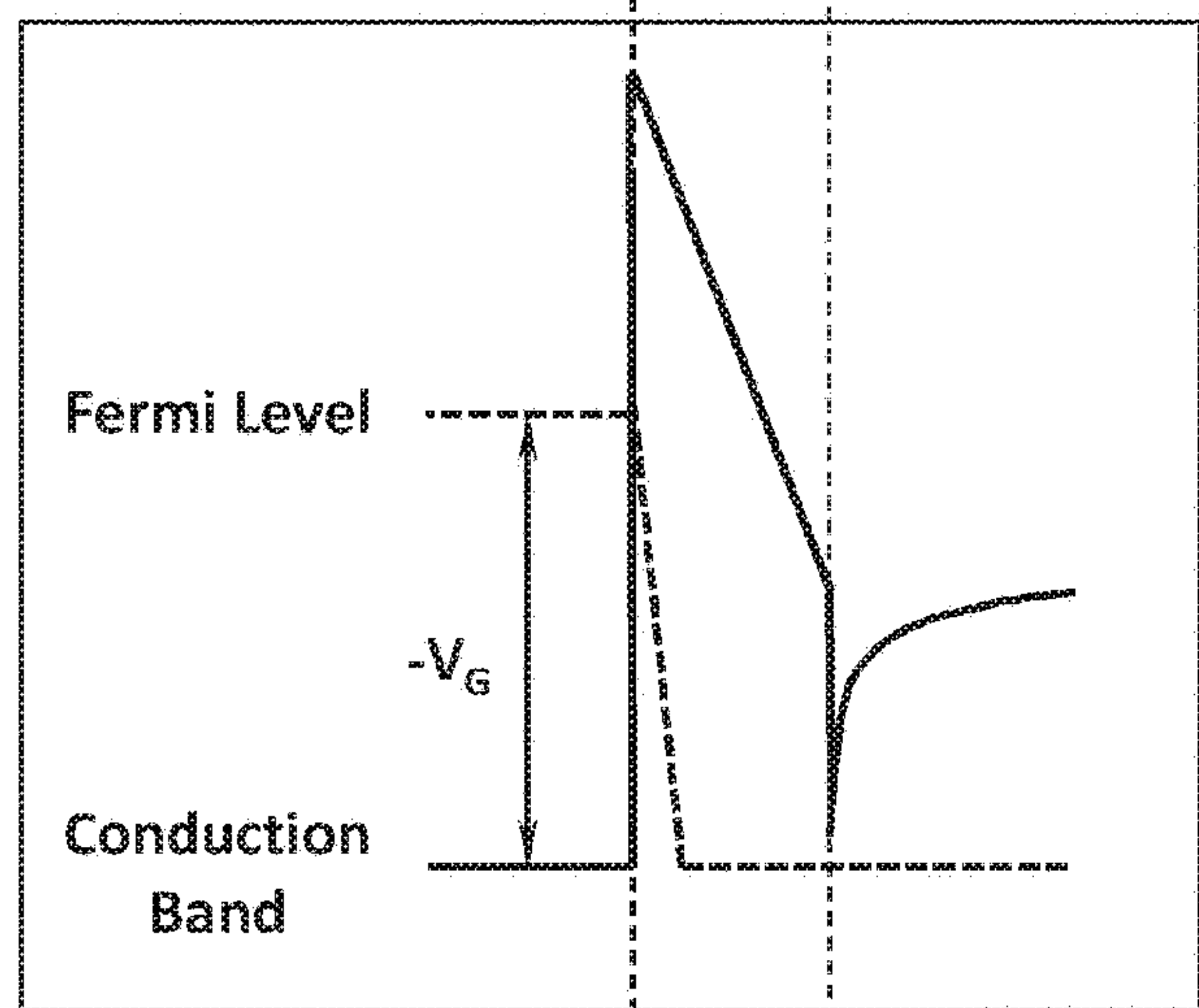


Fig. 1c

$V_G \ll V_T$

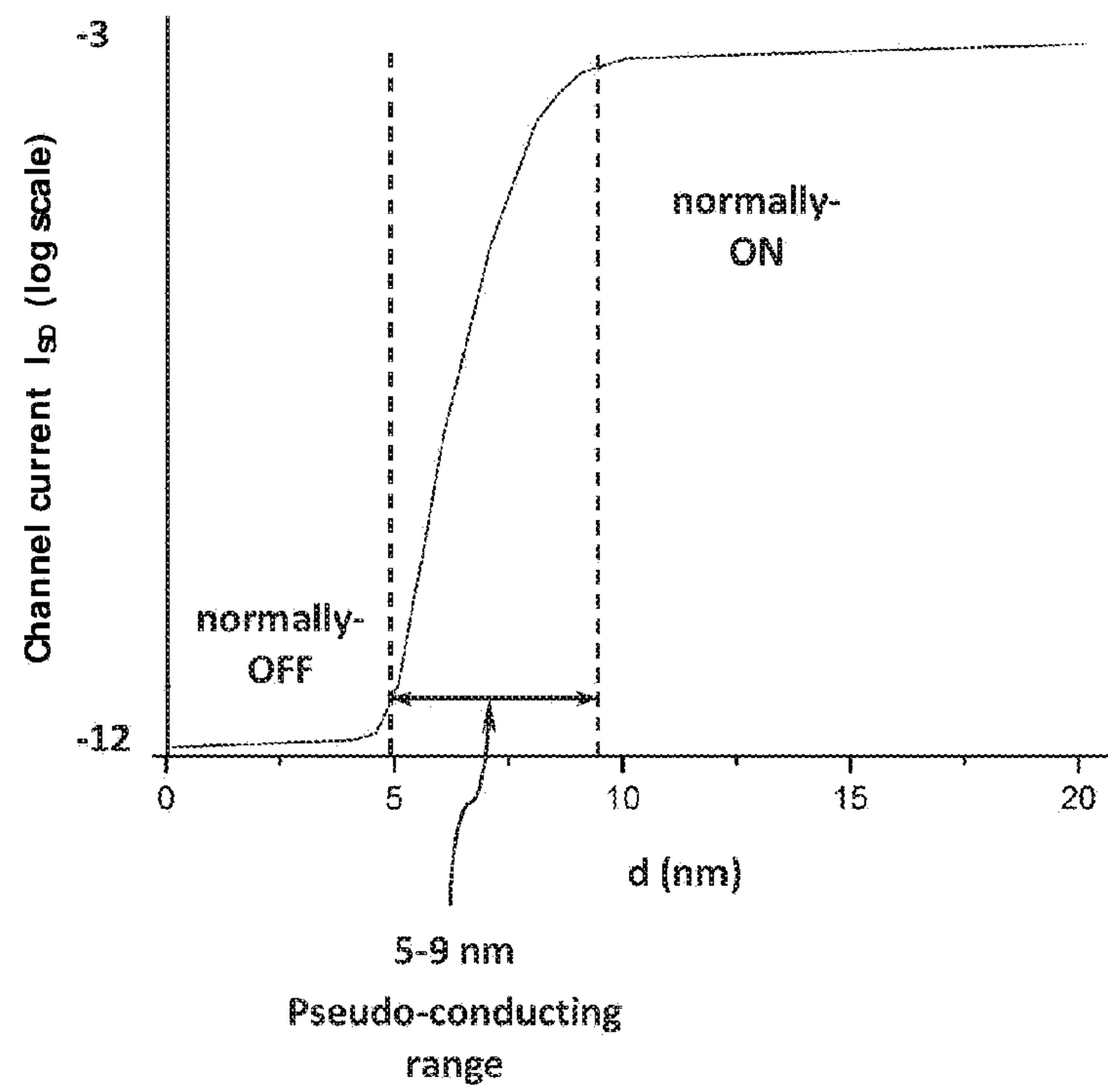
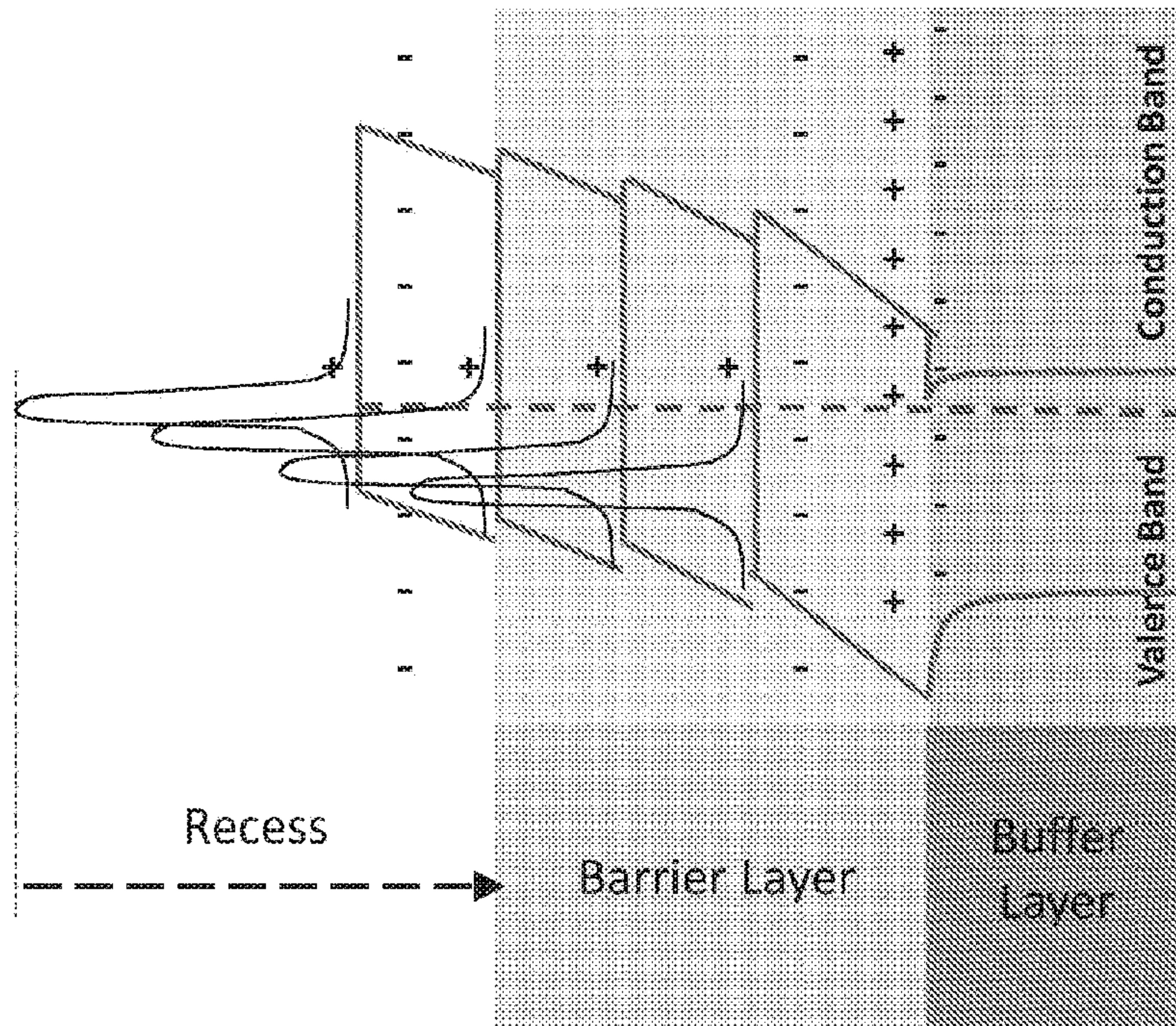


Fig. 2

**Fig. 3**

Normally Grown AlGaIn

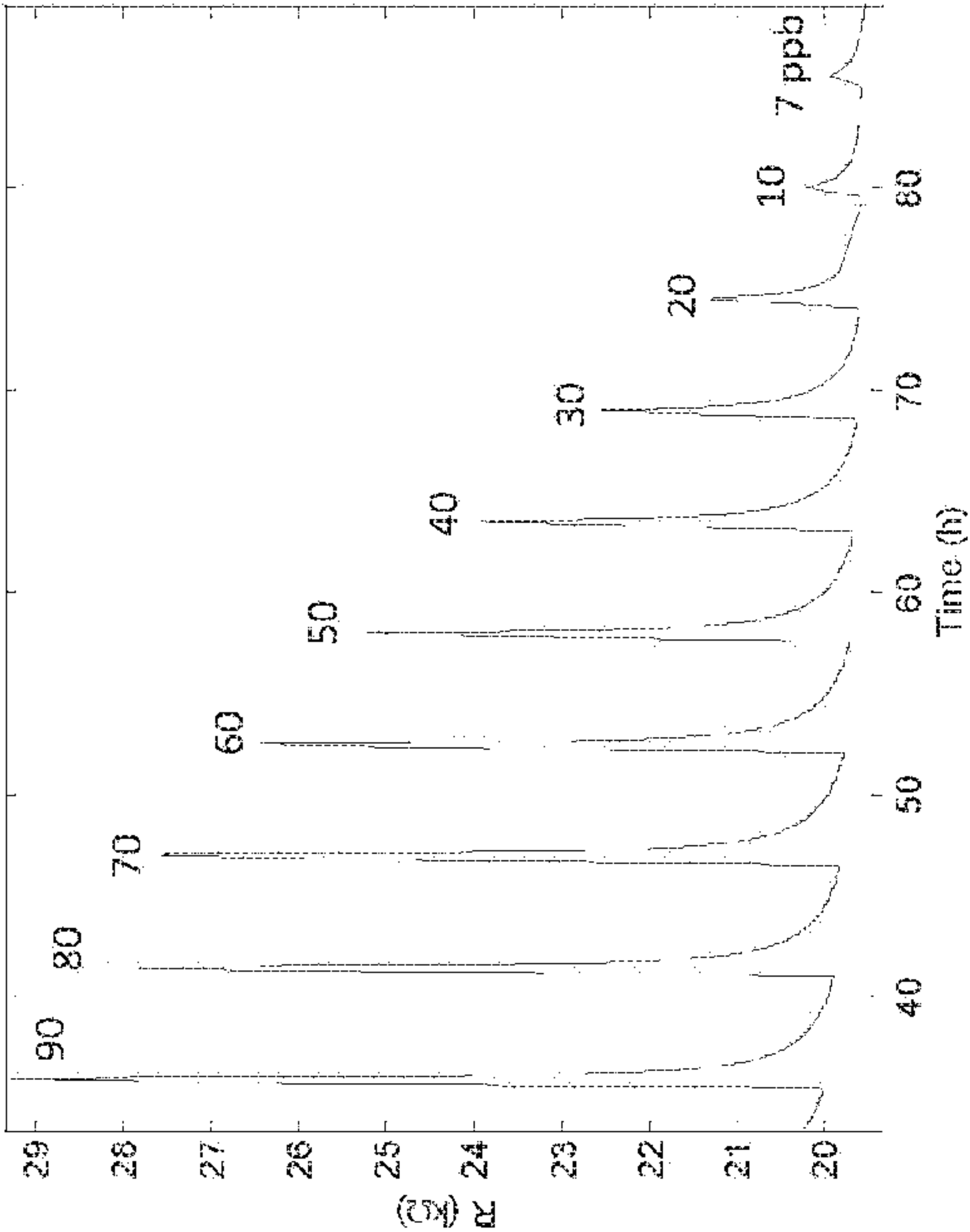


Fig. 4a

Ultra-thin Grown AlGaIn

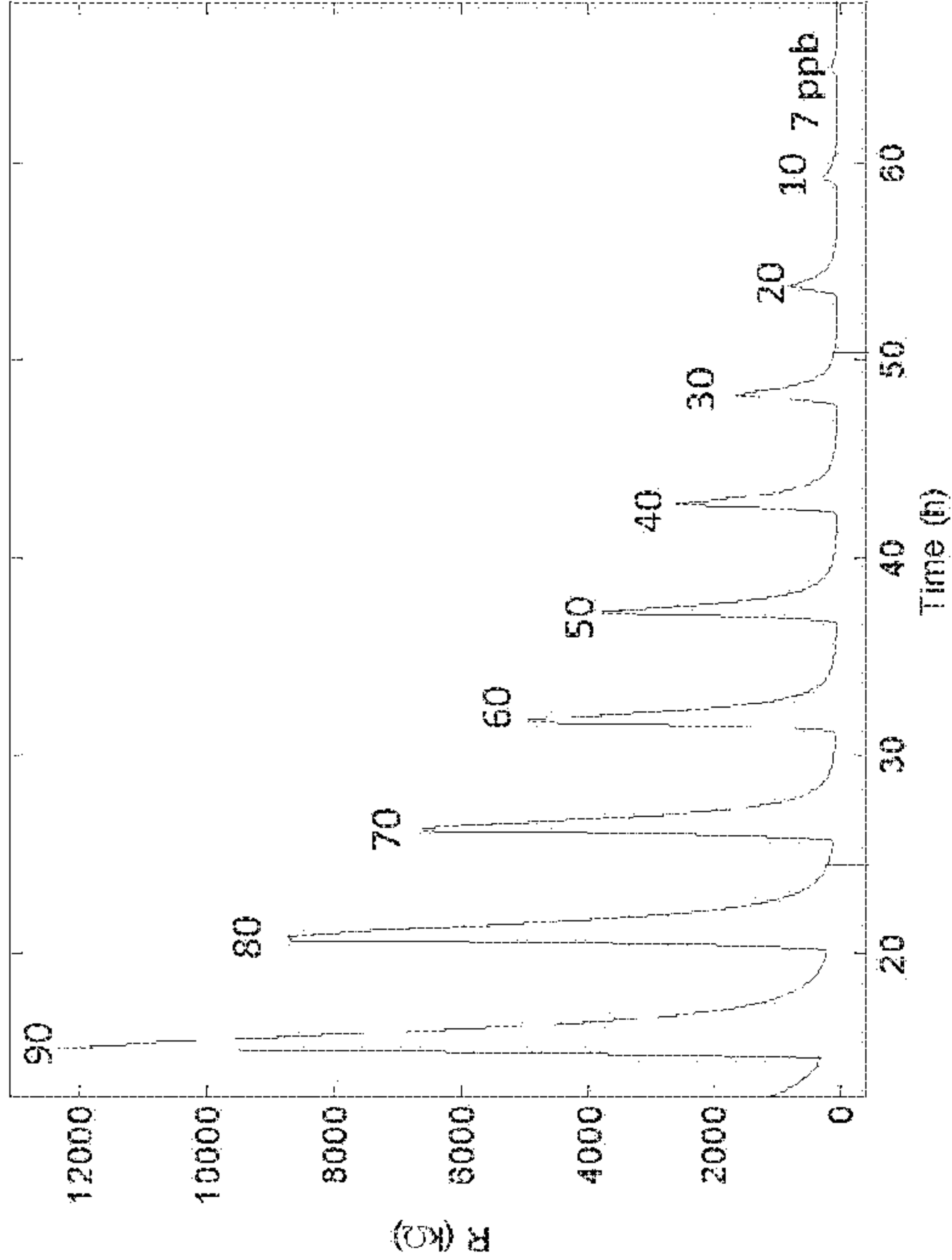


Fig. 4b

Fig. 5a Ga-Face Polarity

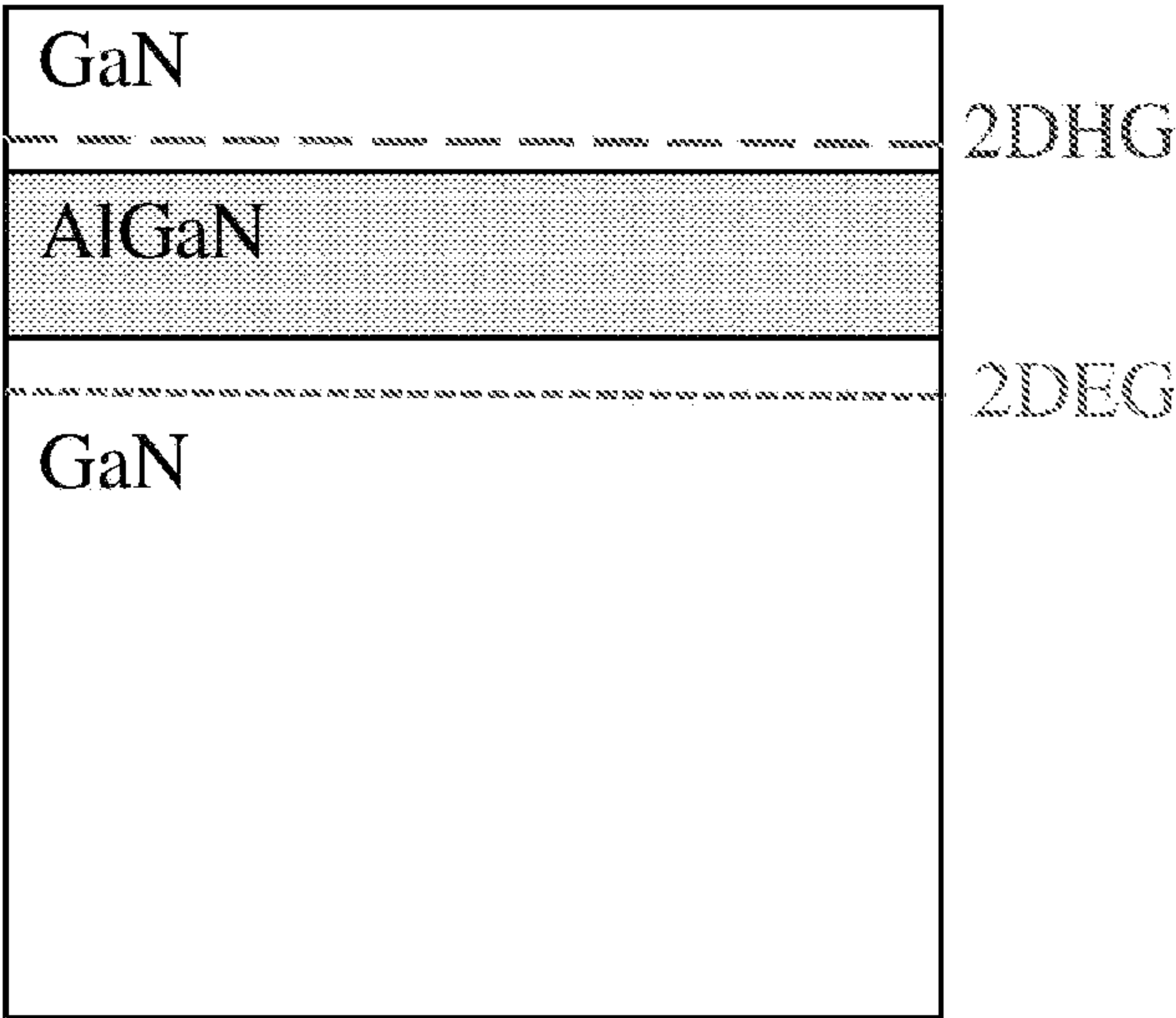
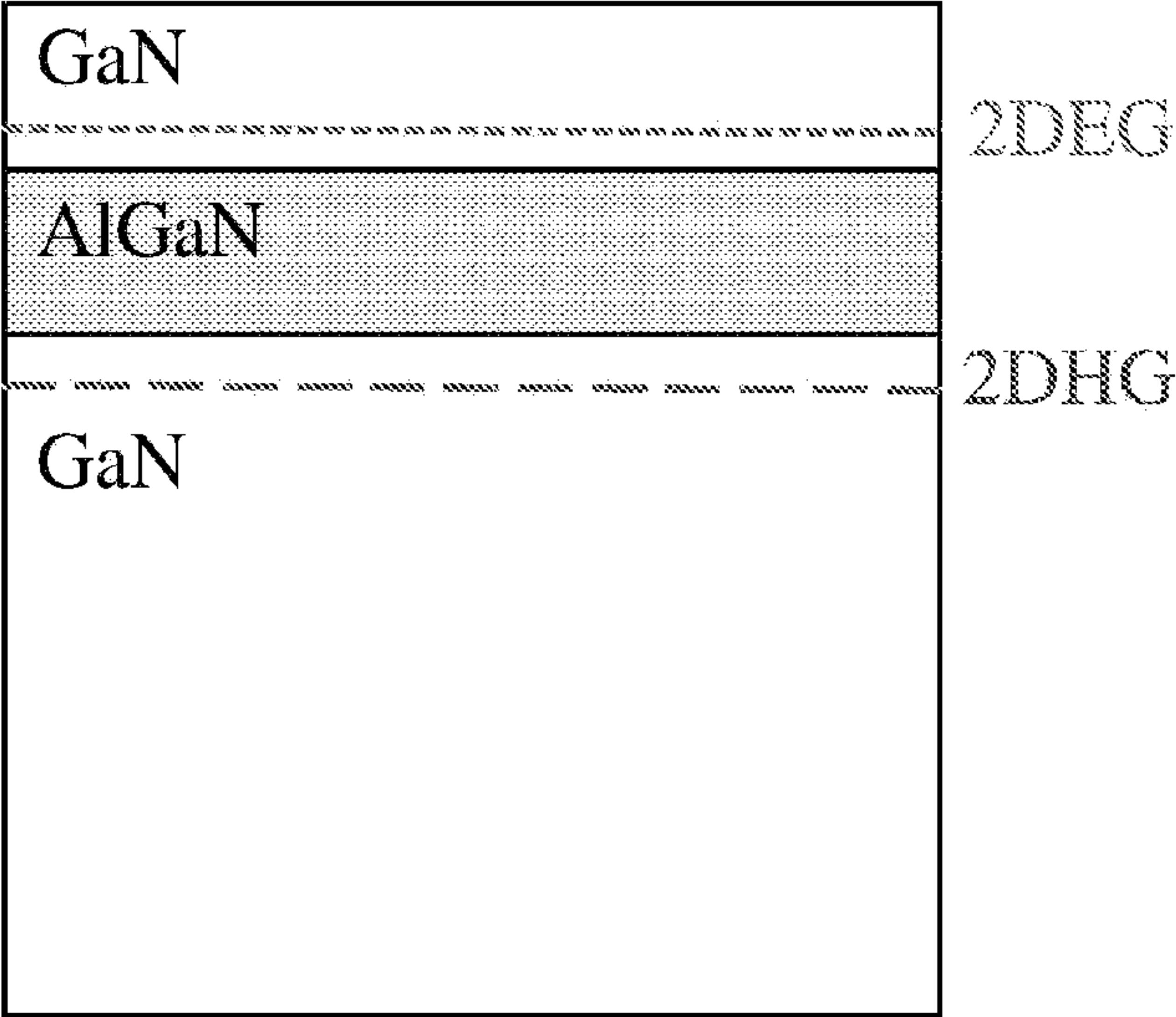


Fig. 5b N-Face Polarity



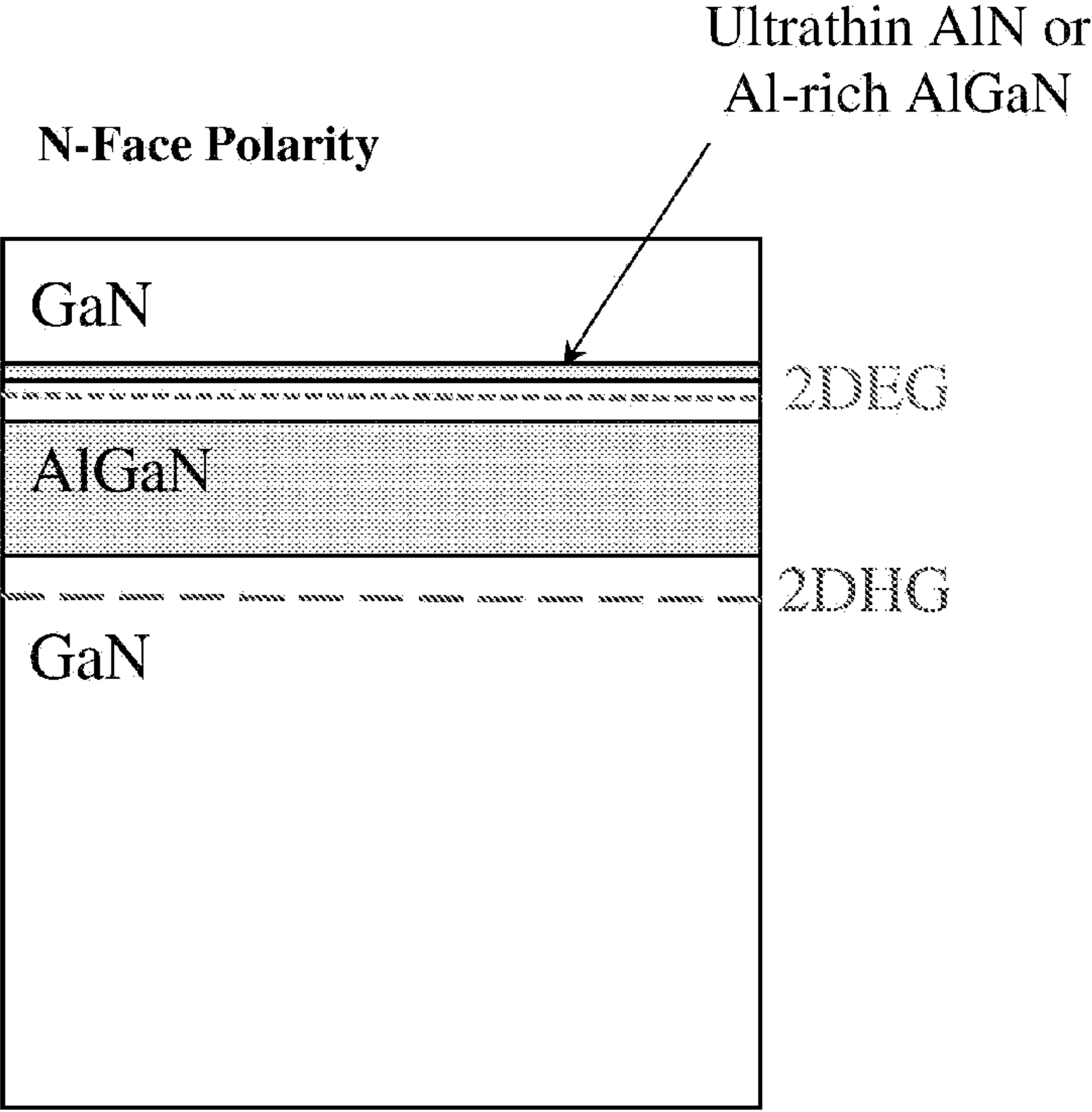


Fig. 6

Fig. 7b

$\lambda = 2 \times d$

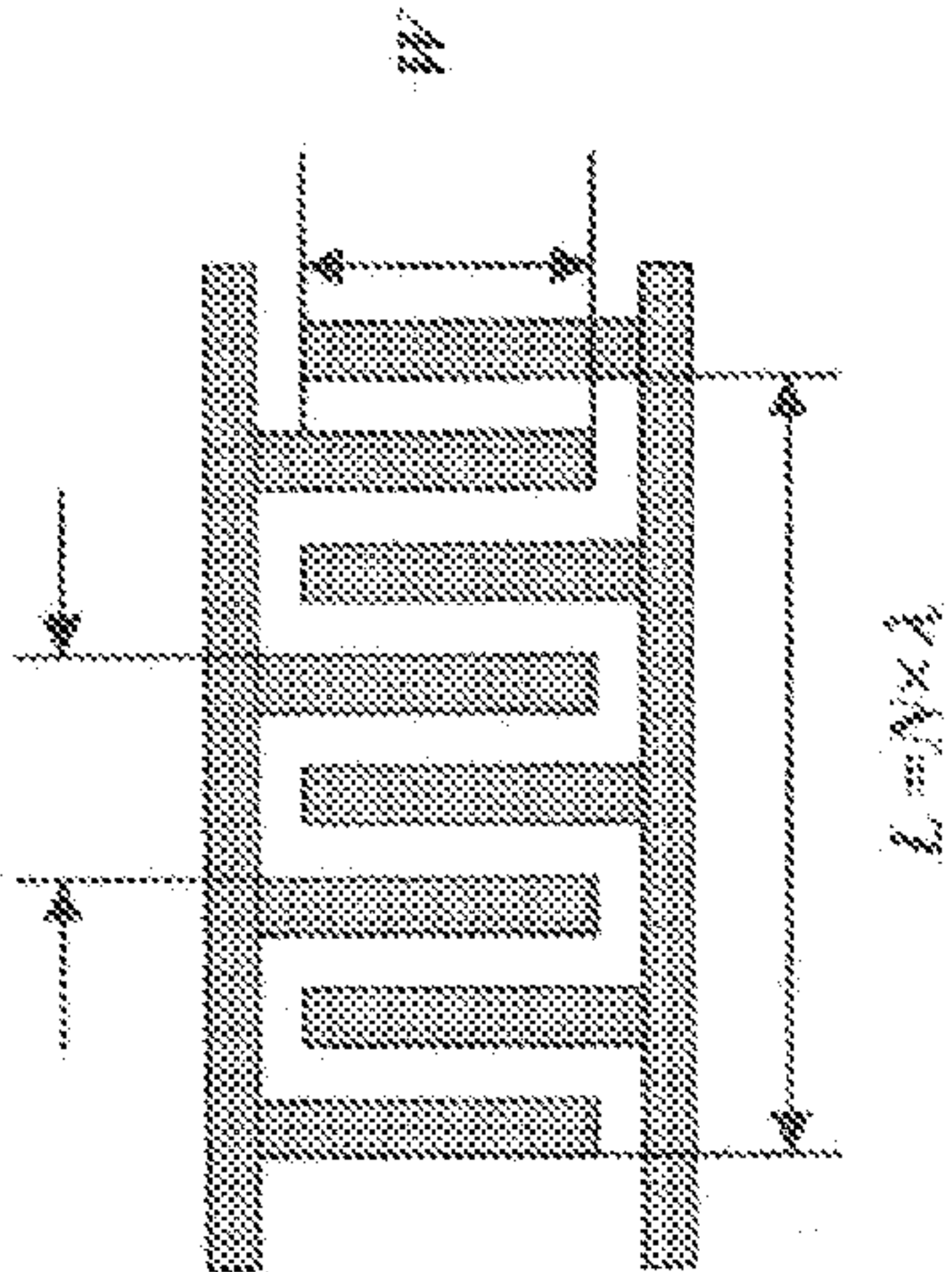


Fig. 7c

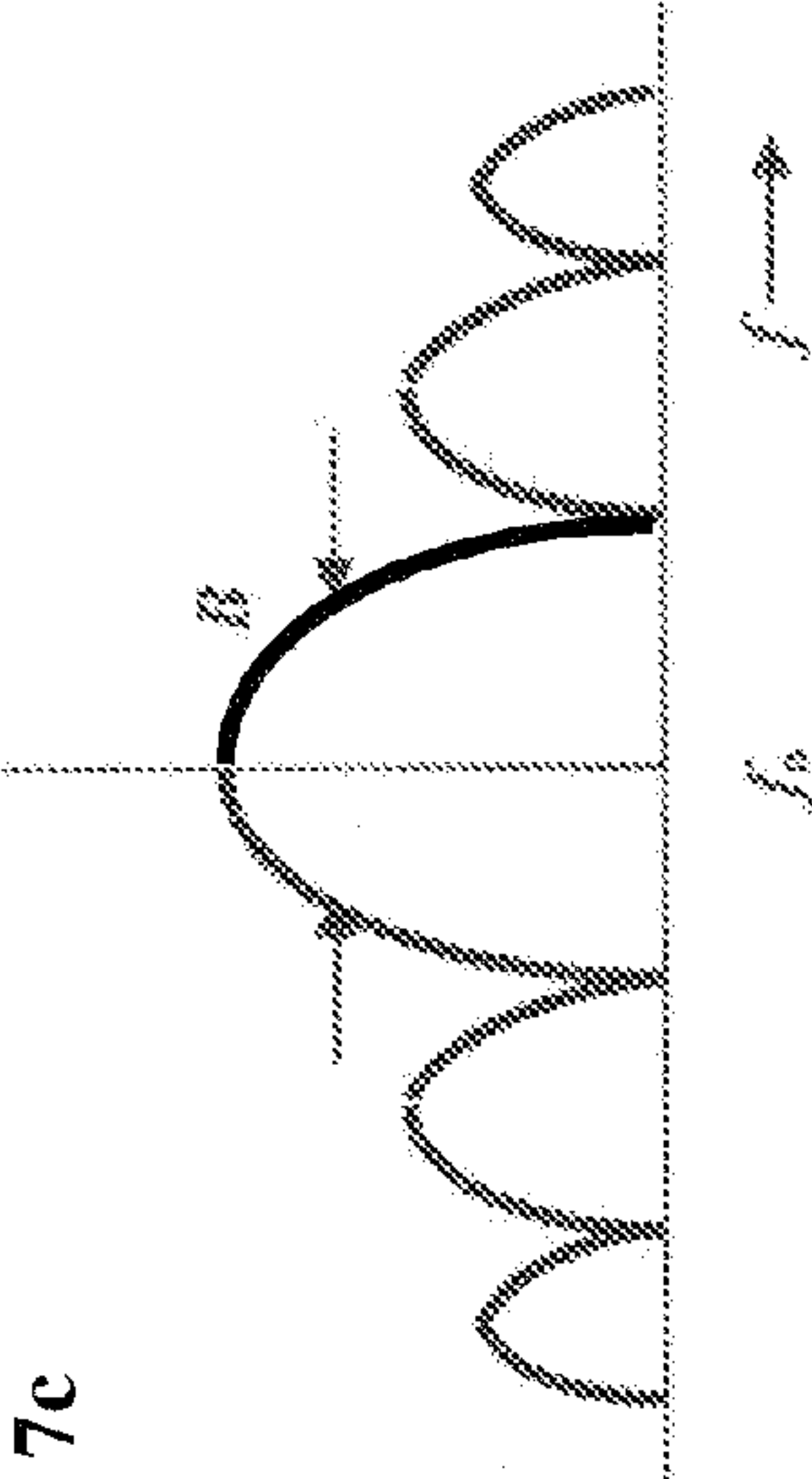
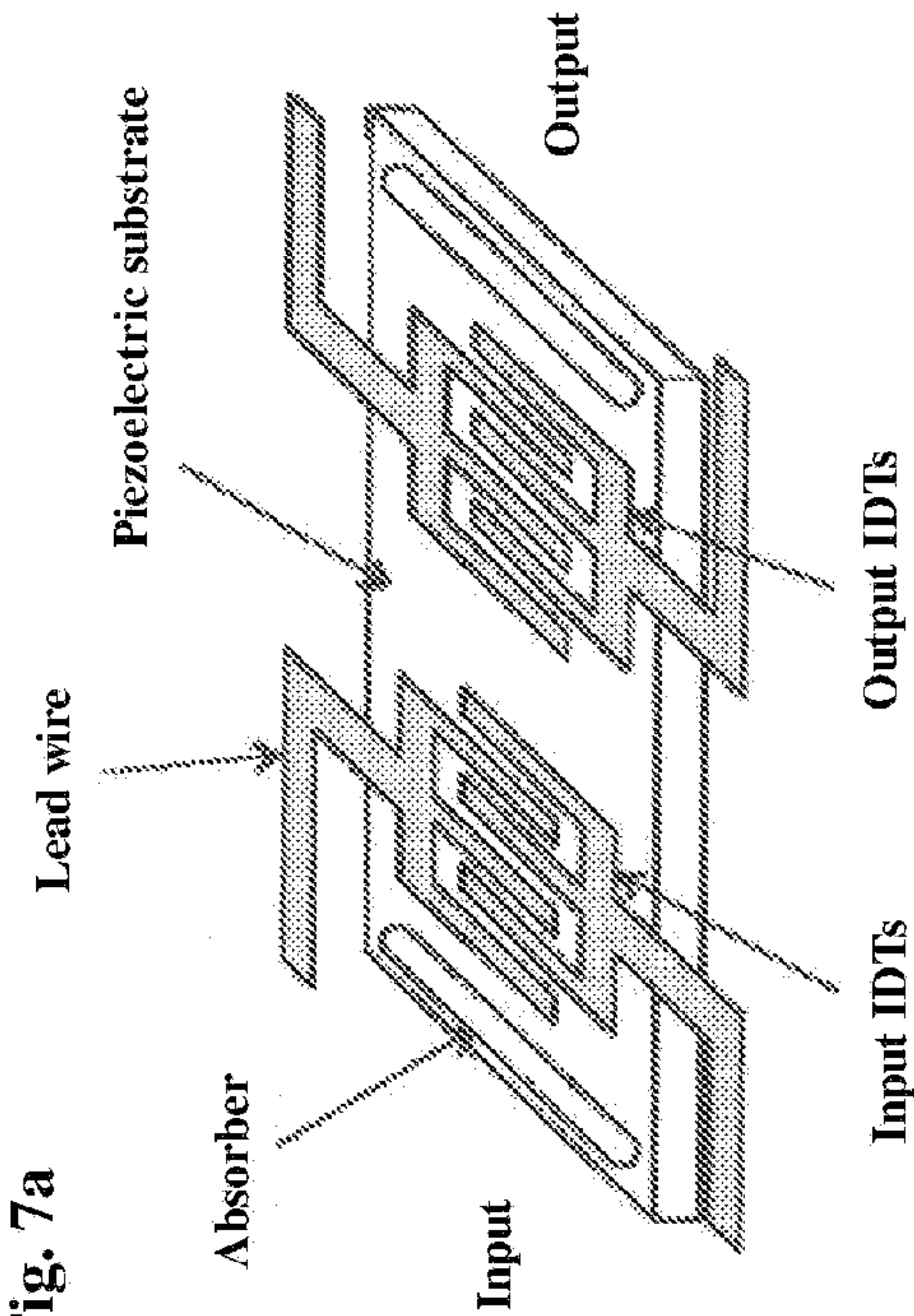


Fig. 7a



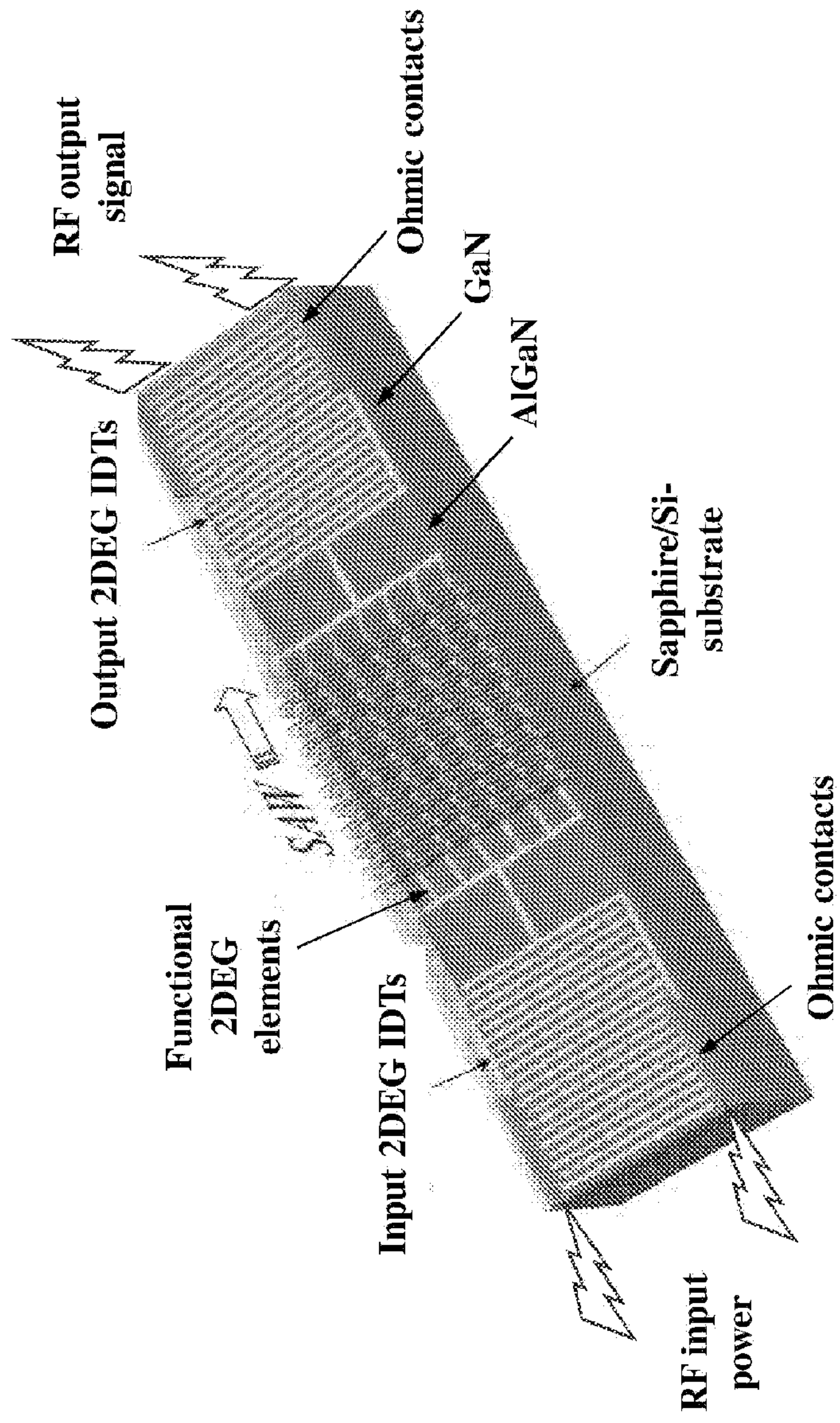
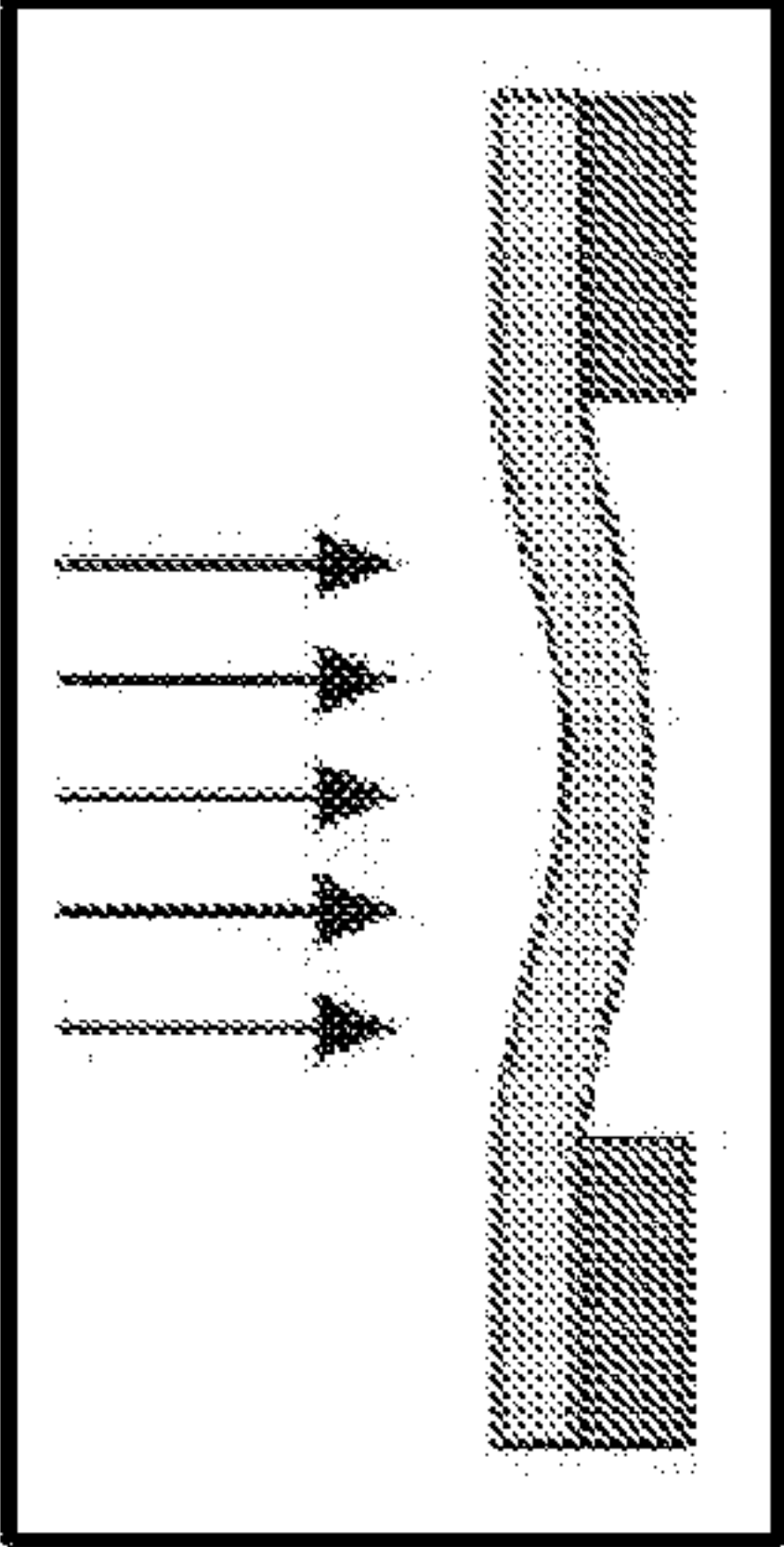
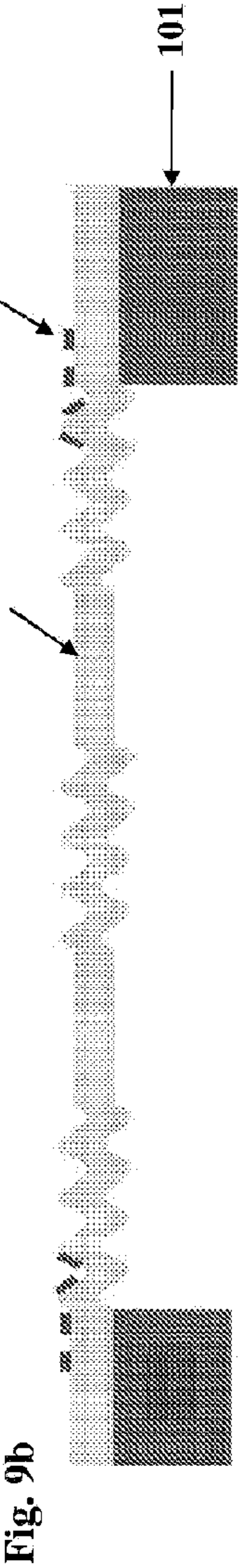
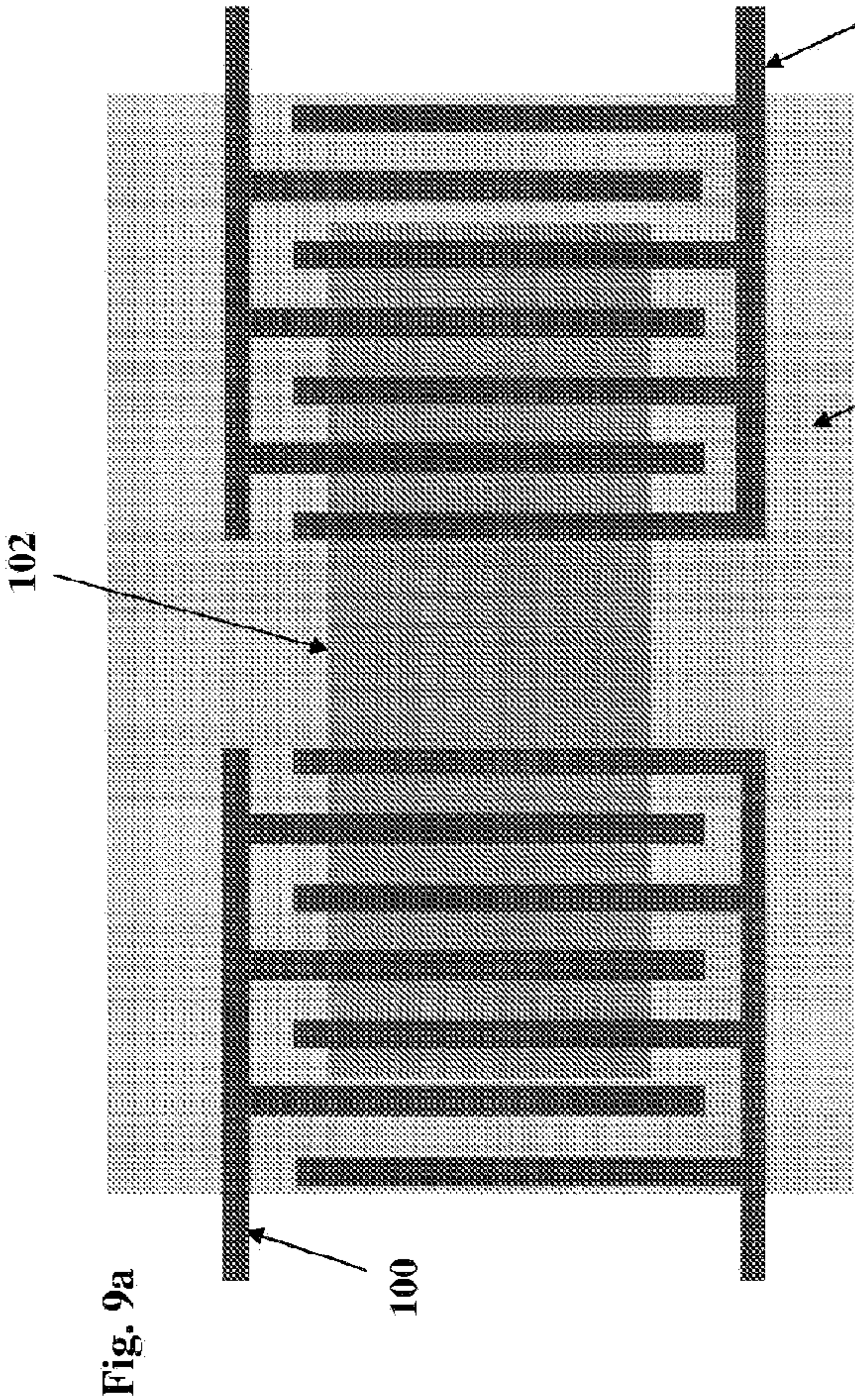


Fig. 8



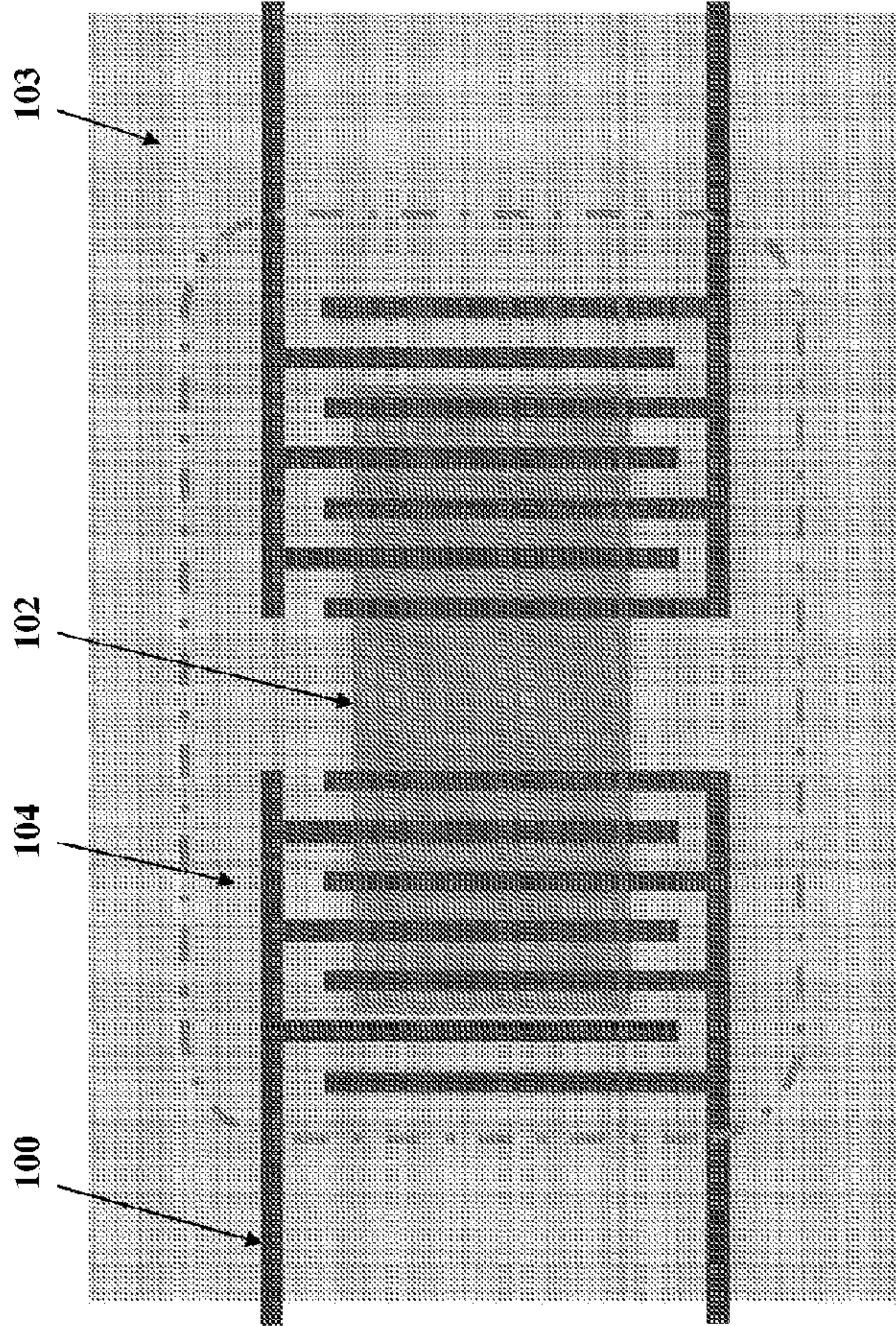


Fig. 10a

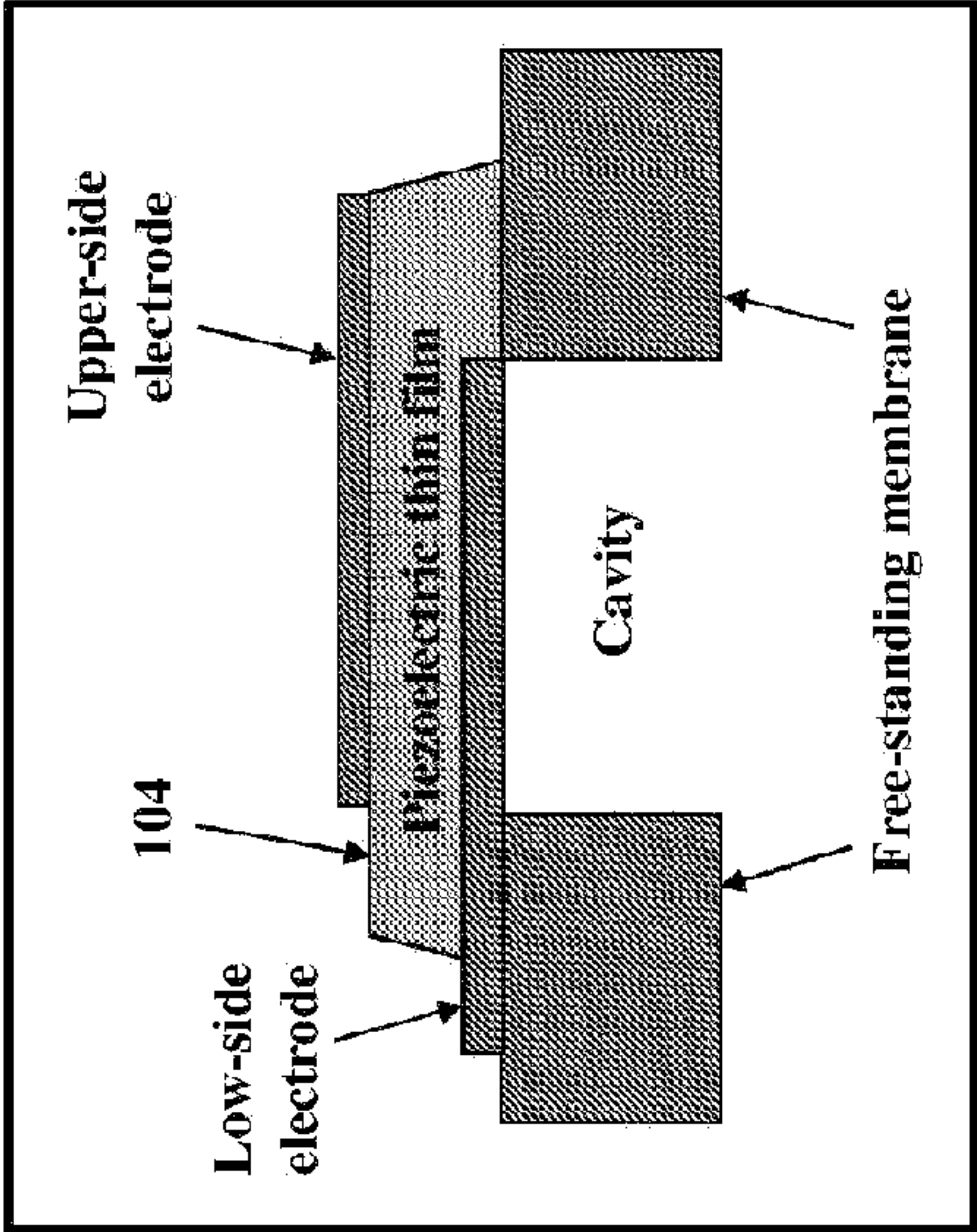


Fig. 10b

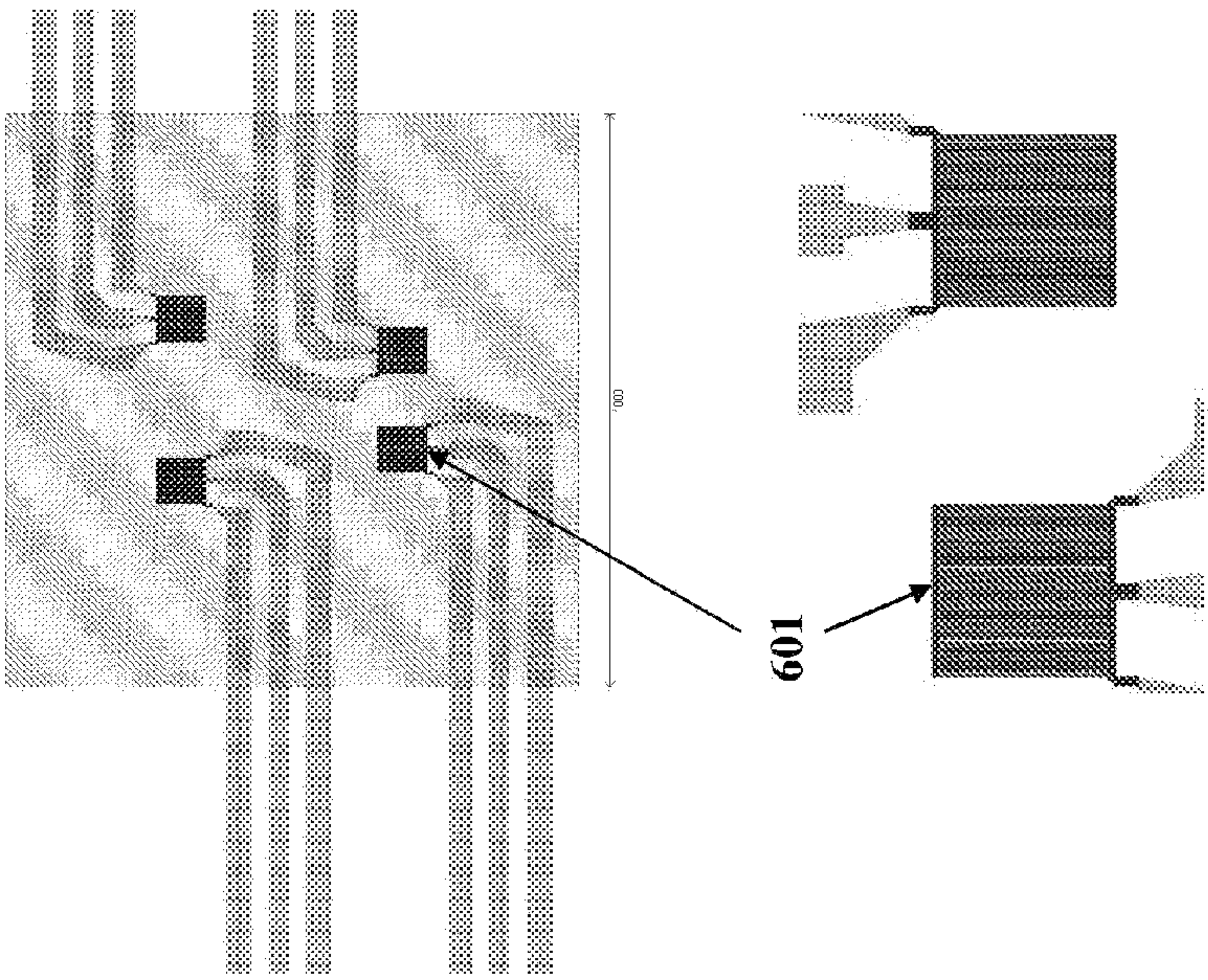
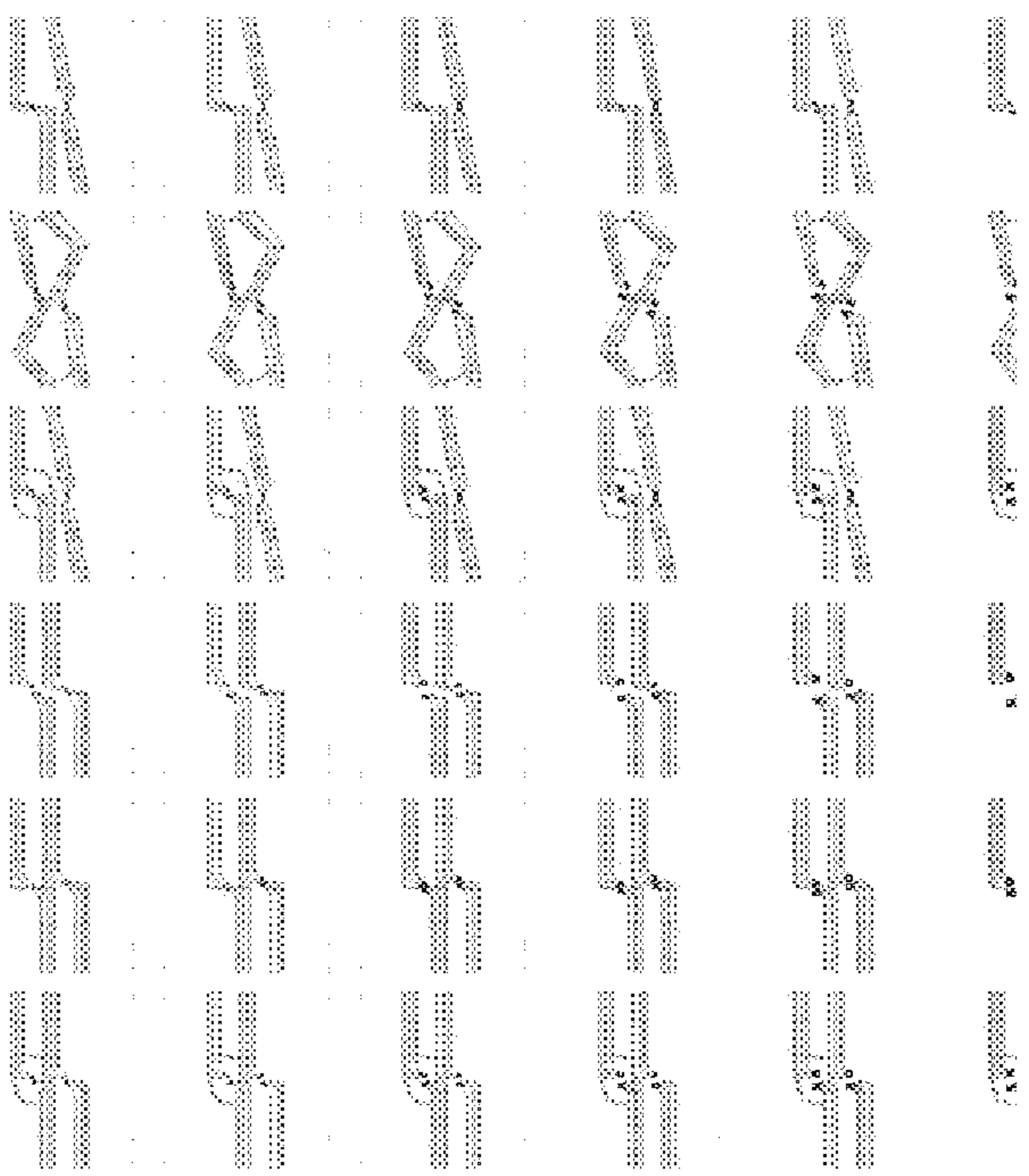


Fig. 11



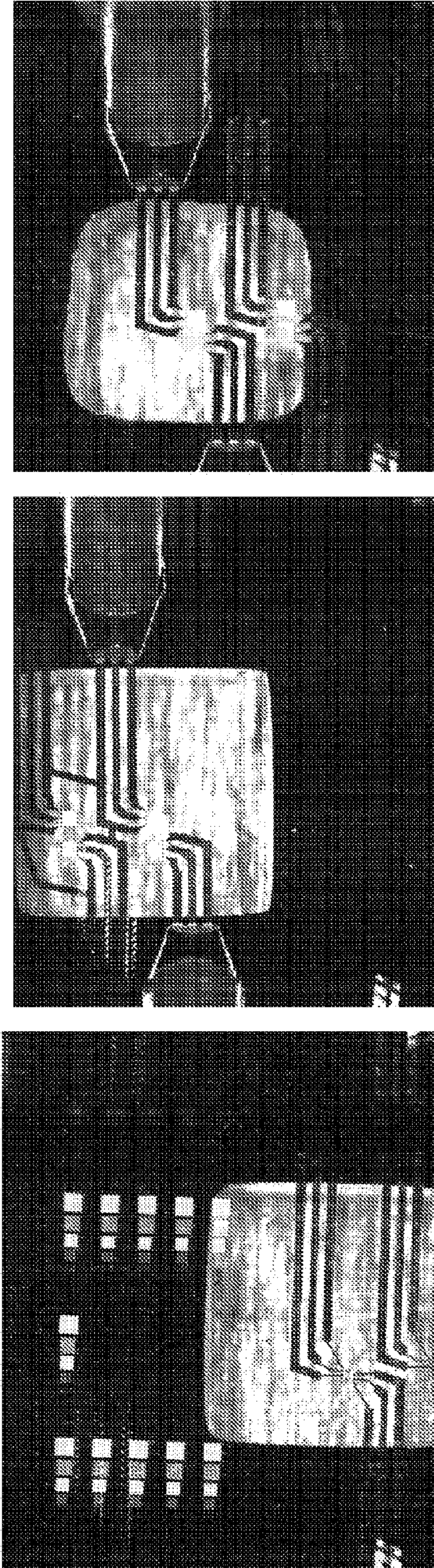


Fig. 13

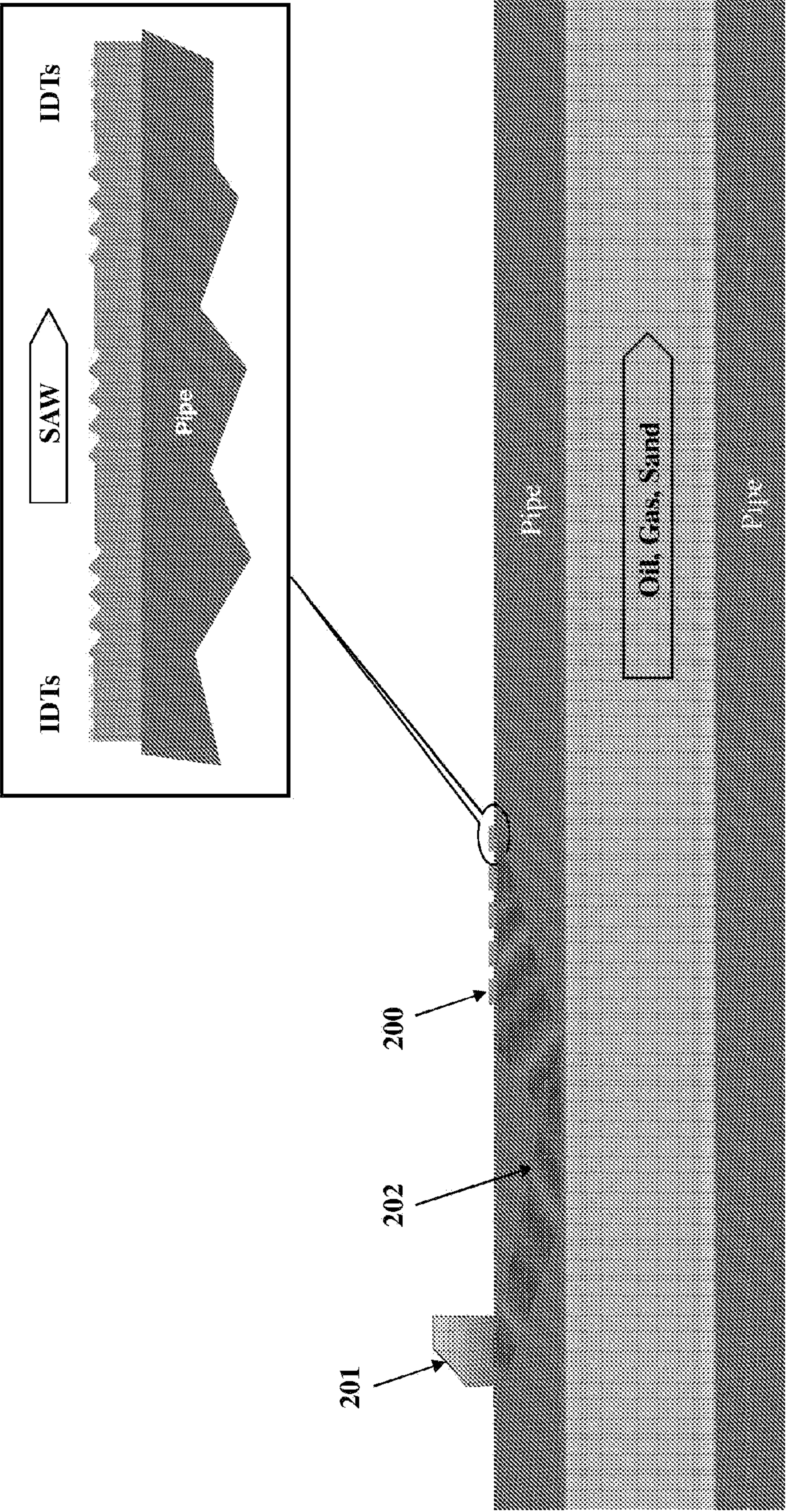


Fig. 14

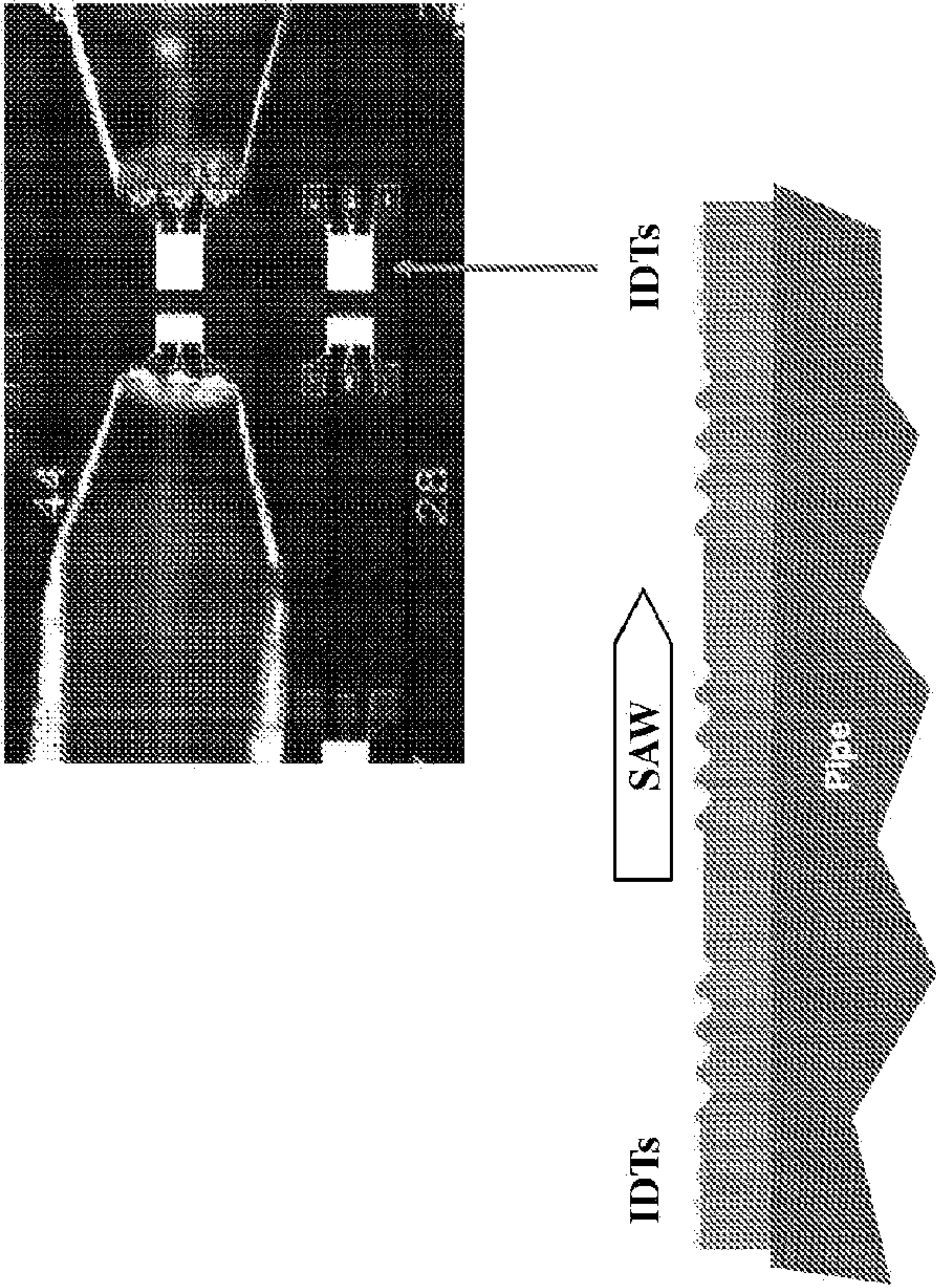


Fig. 15a

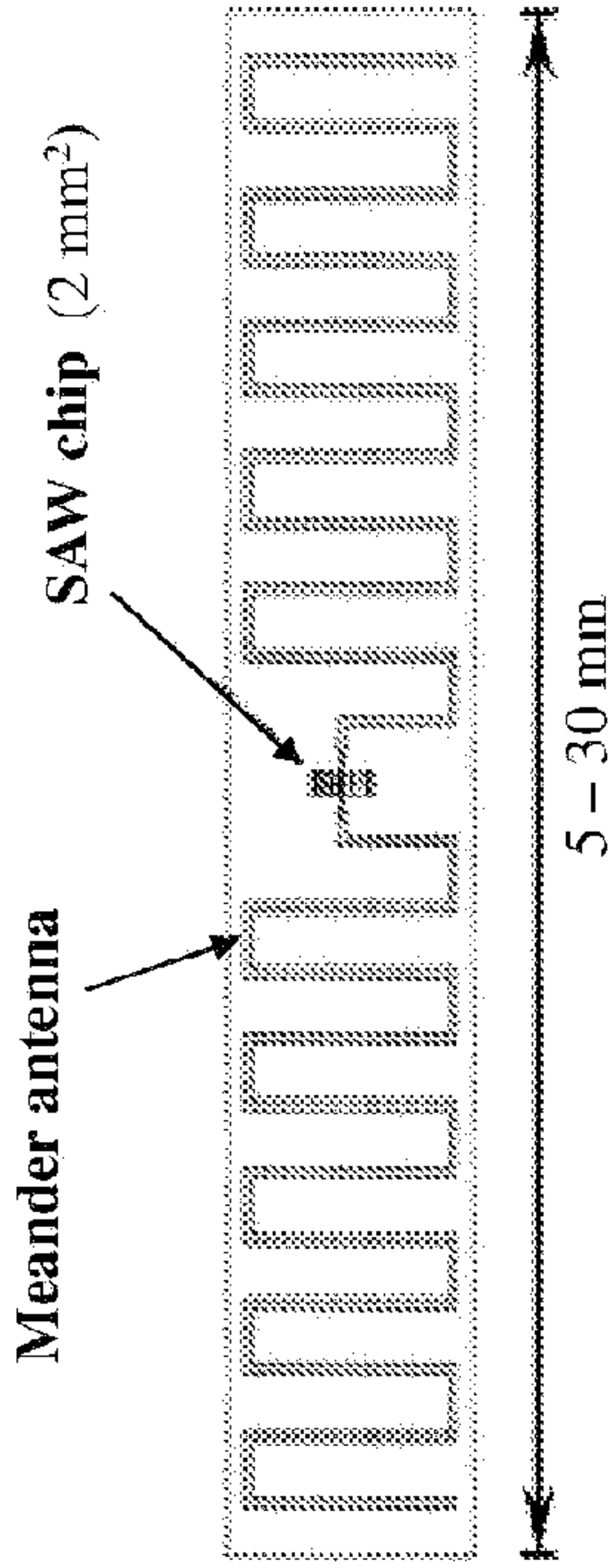


Fig. 15b

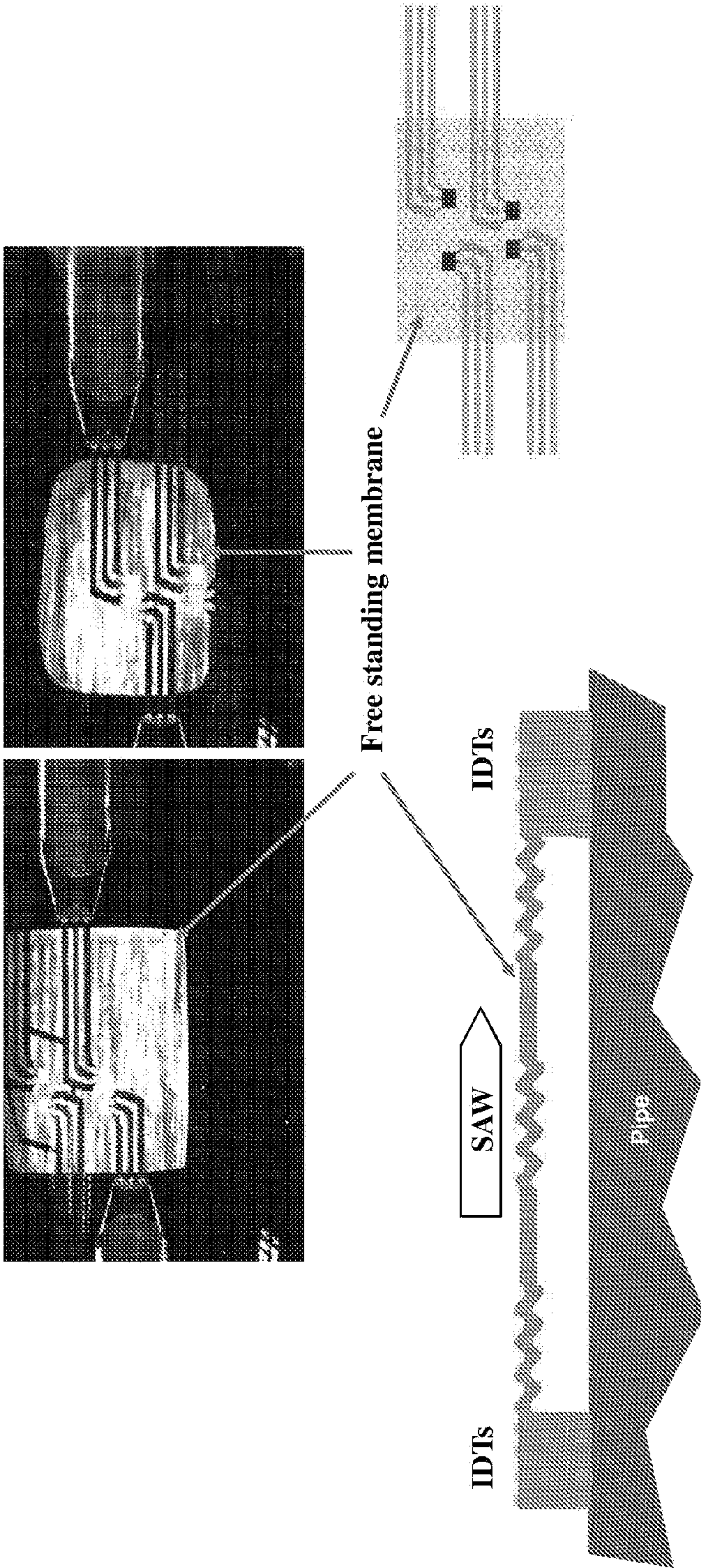


Fig. 16

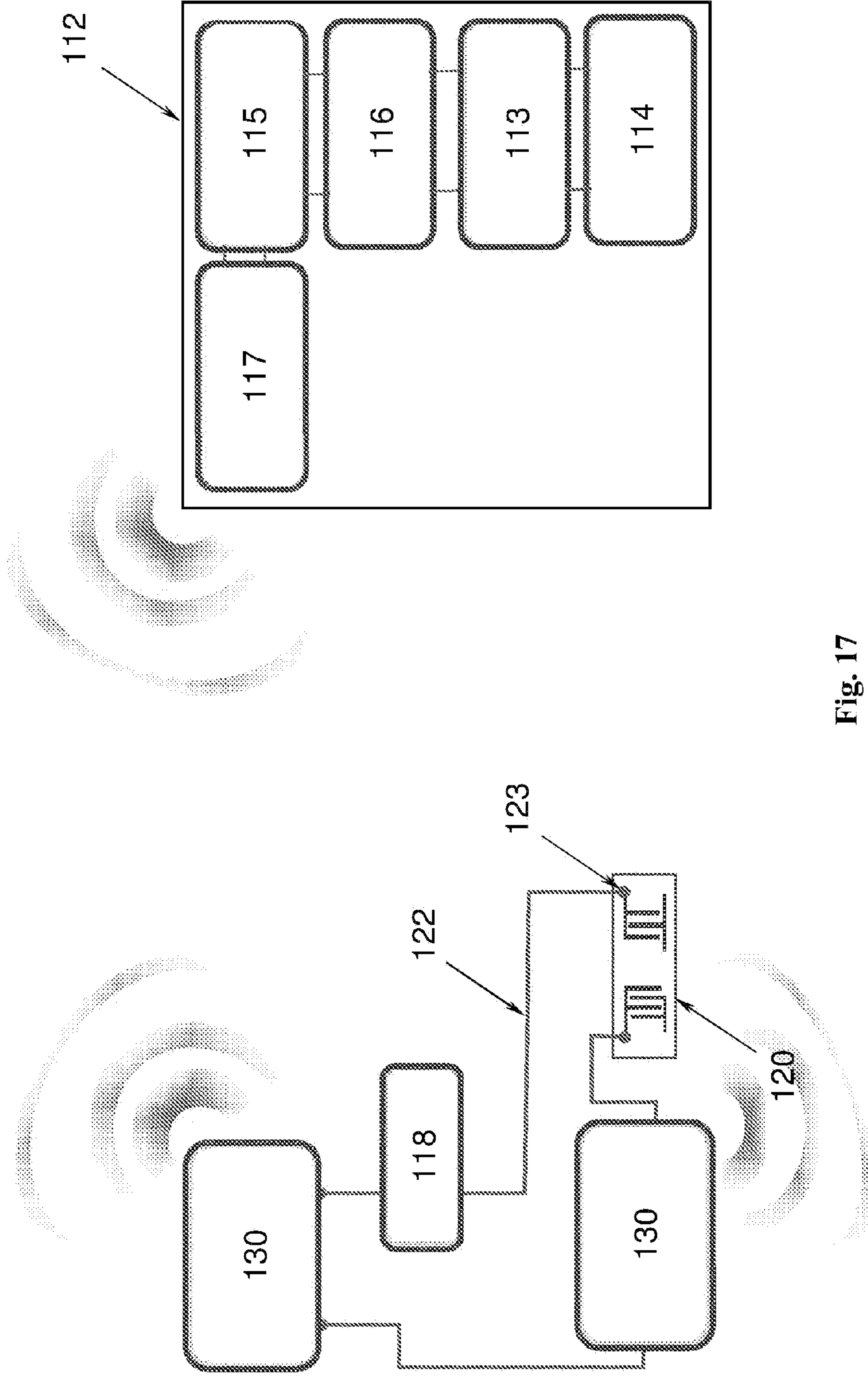


Fig. 17

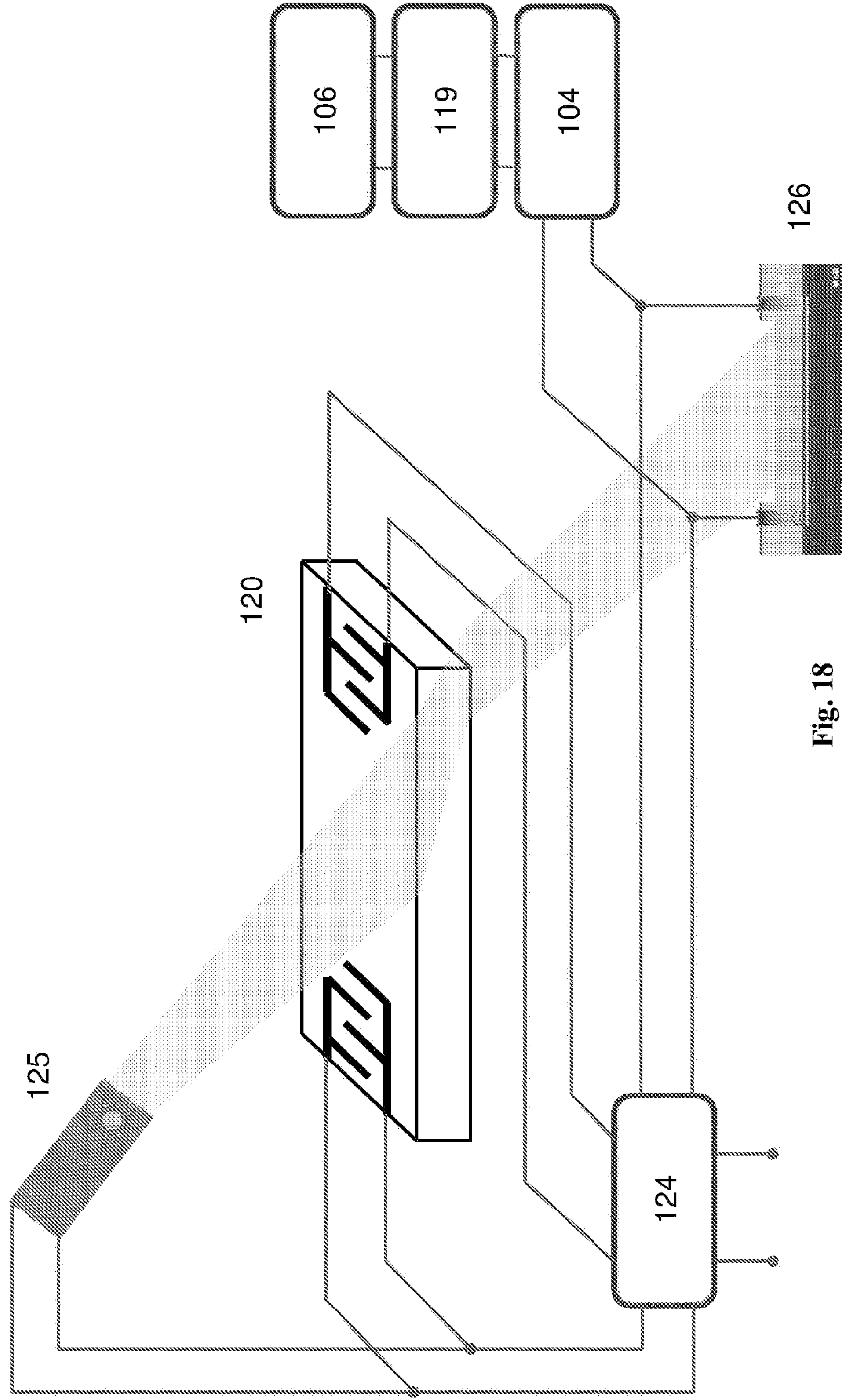


Fig. 18

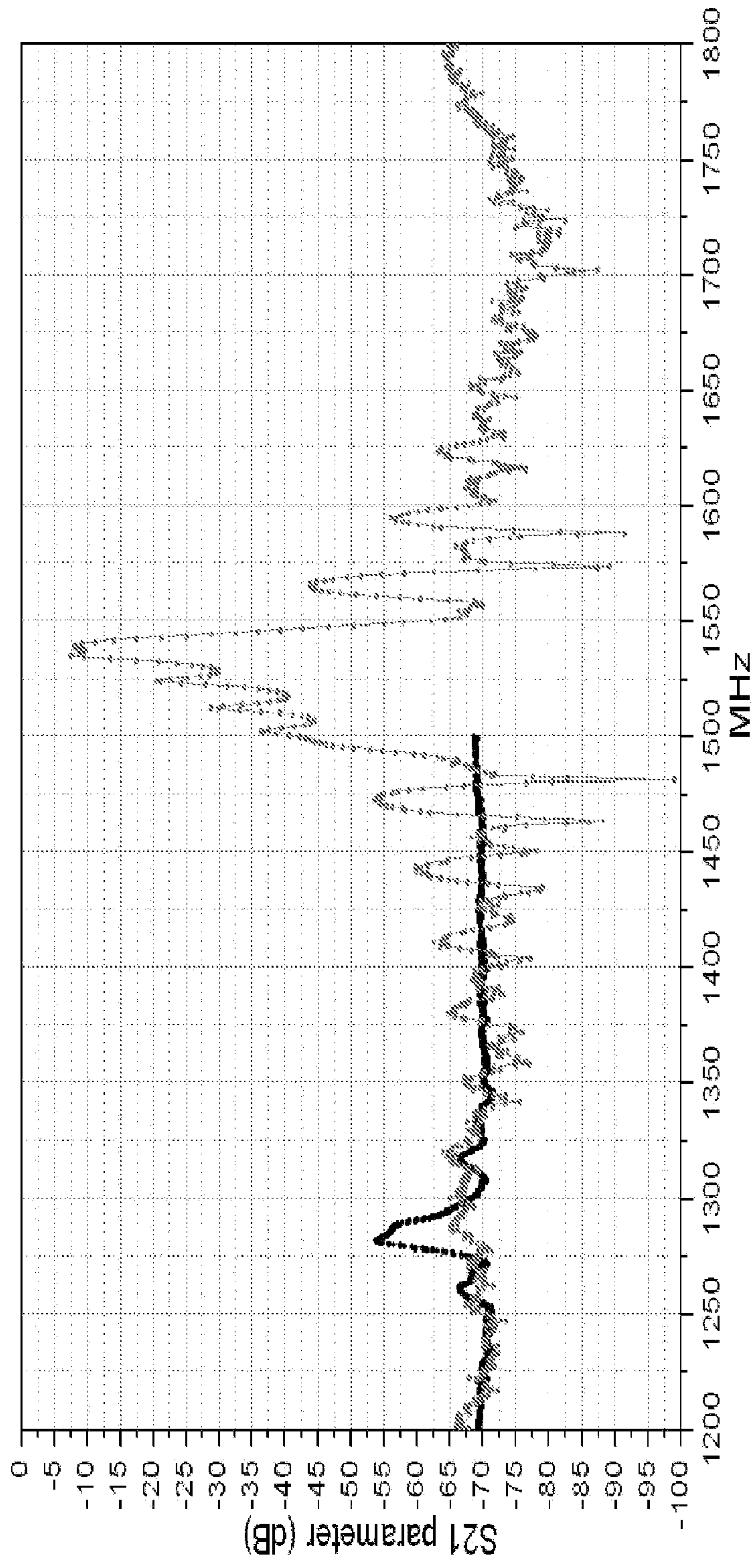


Fig. 19