

[54] **SIGNAL PROCESSING APPARATUS**

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[58] Field of Search. **307/88.3; 330/5.5; 310/8.1**

[56] **References Cited**

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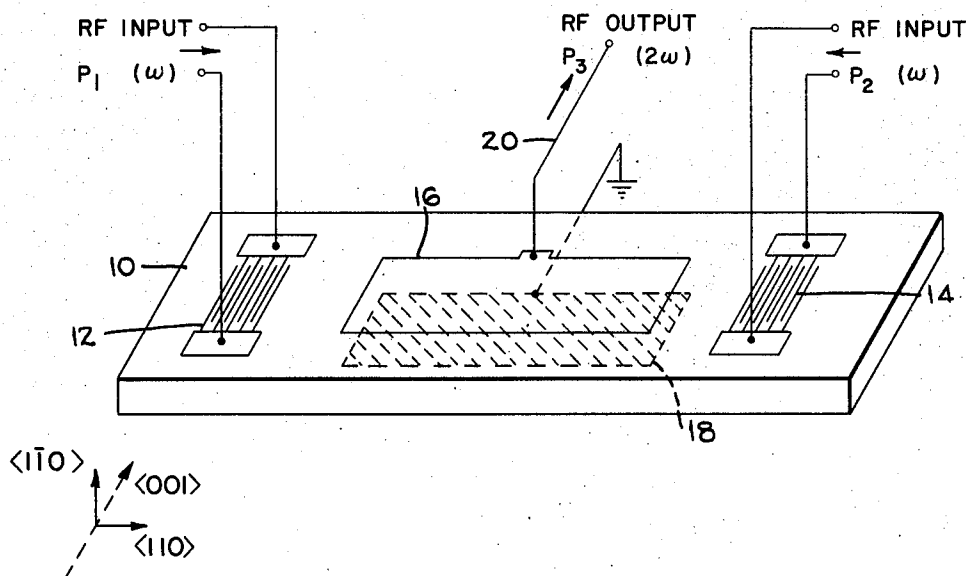
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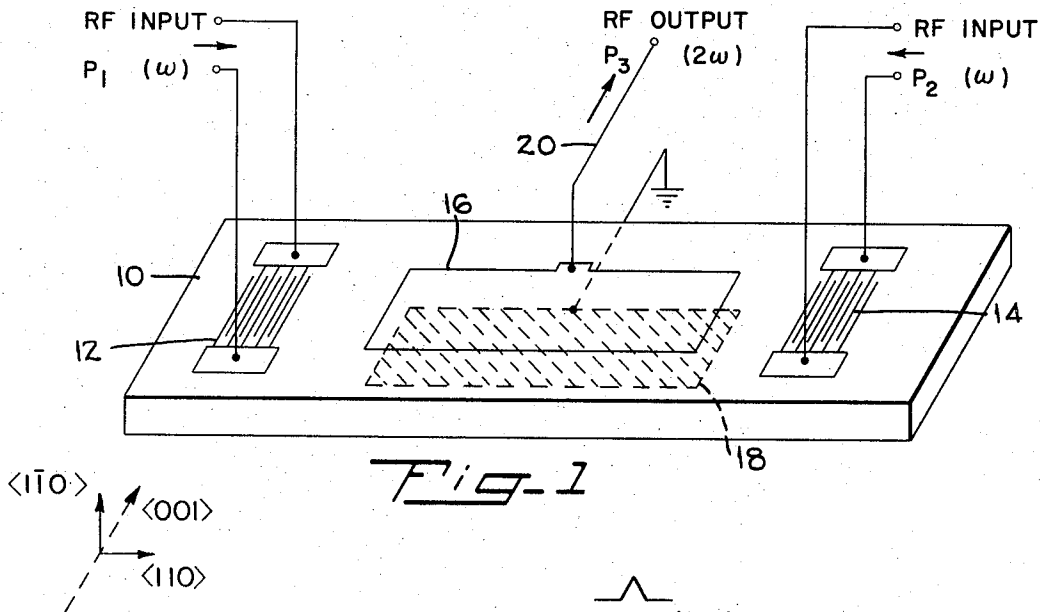
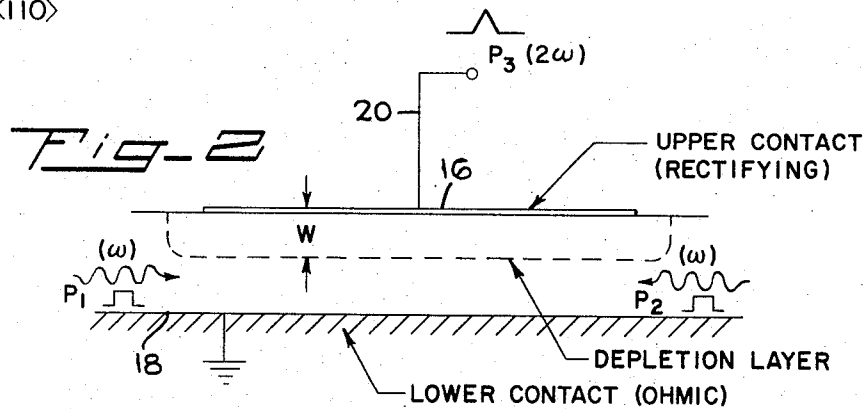
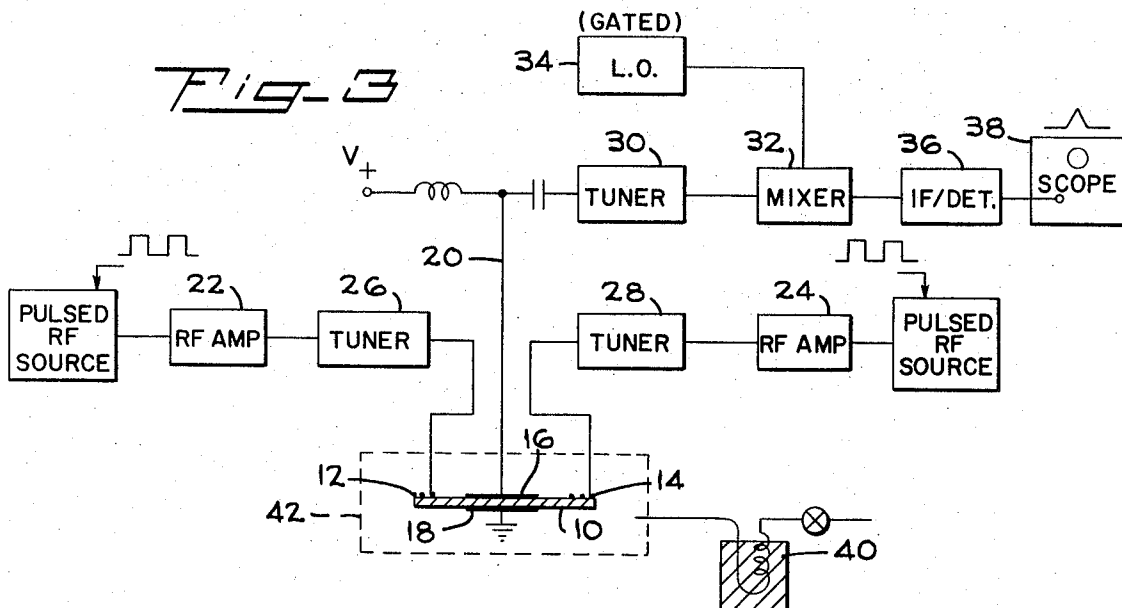
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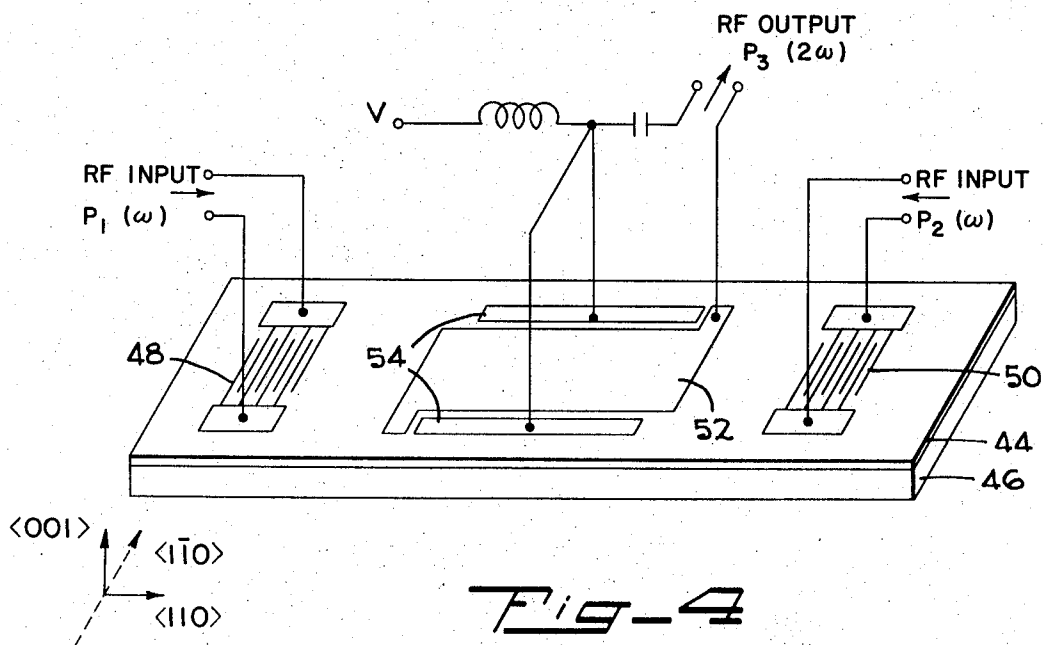
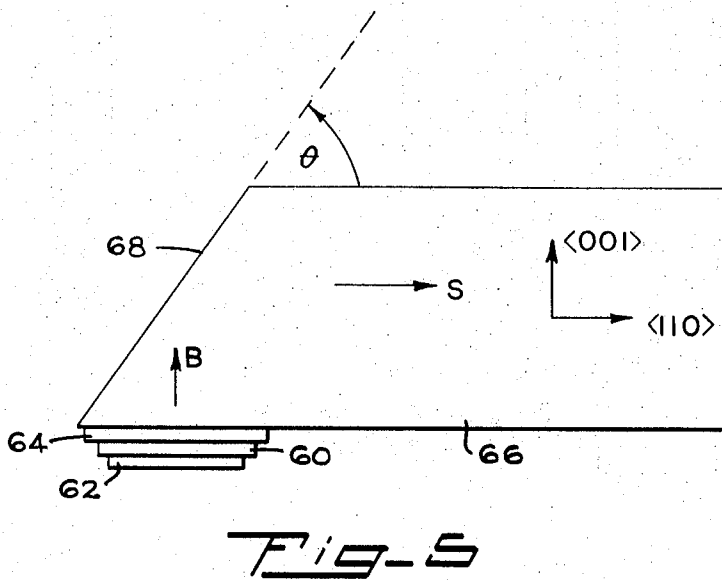
ABSTRACT

Signal processing apparatus wherein acoustic waves are generated and propagated through a piezoelectric semiconductor so as to parametrically interact adjacent to an output electrode so as to provide electric fields which vary the depletion layer adjacent to the output electrode to drive the output circuit.

5 Claims, 5 Drawing Figures







SIGNAL PROCESSING APPARATUS

FIELD OF THE INVENTION

The present invention relates generally to processing of electrical signals of relatively high frequency and more particularly to the processing of such signals through utilization of acoustic waves.

This invention was made in the course of work performed under a contract with the United States Air Force.

BACKGROUND OF THE INVENTION

Considerable experimental effort has been expended to recent years to utilize the interaction of acoustic waves in piezoelectric crystals for carrying out various signal processing operations, as generally reviewed in a recent article in the October, 1972 issue of *SCIENTIFIC AMERICAN*

pages 51-67, entitled "Acoustic Surface Waves".

More specifically, the operation of convolution has been attained utilizing the interaction of bulk acoustic waves as explained in the Quate-Thompson article in *APPLIED PHYSICS LETTERS*, Vol. 16, No. 12, pages 494-496 (1970), such operation relying on the nonlinearities in the elastic behavior of strongly piezoelectric crystals for which departures from Hooke's Law become significant at strains of 10^{-4} - 10^{-5} . Yet more recently, as described in the Luukkala-Kino article in *APPLIED PHYSICS LETTERS*, Vol. 18, No. 9, pages 393-394 (1971), the same principle of nonlinear elastic behavior in piezoelectric crystals has been utilized with acoustic surface or Rayleigh waves. While the operations have been successful both with the bulk and surface acoustic waves, considerable power was required to operate at the nonlinear strain levels required.

SUMMARY OF THE PRESENT INVENTION

It is accordingly the general objective of the present invention to provide an acoustic wave apparatus arranged to carry out convolution or other signal processes more efficiently and at lower input power levels through interaction of the electric fields associated with the acoustic waves rather than the strains. Generally, this objective is achieved by associating a metal electrode with a piezoelectric semiconductor within which the acoustic waves interact to provide electrical nonlinearity adjacent to the surface due to variations in the depletion layer associated with the metal-semiconductor contact resultant from variations in the electric field associated with the acoustic waves in the semiconductor.

In a preferred arrangement, like pulses of electromagnetic energy at the same frequency are delivered to interdigital transducers on the surface of a piezoelectric semiconductor such as GaAs (gallium arsenide), whose crystalline orientation is such that oppositely propagating acoustic surface shear waves are generated. These surface shear waves are described in an article by J. L. Bleustein in *APPLIED PHYSICS LETTERS*, Vol. 13, No. 12, pages 412-413 (1968) and have a relatively great penetration depth particularly into a weakly piezoelectric crystal such as GaAs, typically approximating 200 wavelengths, as compared to the rather shallow penetration depth of no more than 1 or 2 wavelengths of the more conventional Rayleigh waves. In addition, these surface shear waves propagate

with only one component of particle motion which is parallel to the surface and perpendicular to the sagittal plane of the crystal and are accordingly free from surface environmental effects, such as the surface finish of the crystal or adjacent environmental conditions.

The two acoustic surface shear waves propagate to an overlapping position whereat a parametric interaction occurs so that, as opposed to the generation of the product of the strains as utilized in the mentioned Quate-Thompson bulk wave arrangement and the Luukkala-Kino surface wave apparatus, the electrical or space charge nonlinearities of the electric fields are utilized to vary the width of the electrical depletion layer formed by a rectifying surface electrode positioned adjacent the semiconductor. In the case described, where the frequencies of the two input waves are identical, the parametric interaction conditions are such that no spatial variation in the electric field exists and such output electrode can be in the form of a simple rectifying plate composed of aluminum or other material which actually forms a Schottky barrier contact adjacent to the propagating surface face of the crystal. An ohmic contact of gold or other material is formed on the opposite face of the crystal and initial establishment of a predetermined width of the depletion layer can be obtained by application of a suitable DC bias thereacross. As the waves interact to vary the transverse electric fields, the width of the depletion layer varies and this, in turn, will drive the output circuit connected to the output electrode. The described interaction is highly efficient and it has been found experimentally that relatively low input powers will allow the production of a significant convolution output.

The output power has also been found in some cases to be dependent upon temperature and because of the aforementioned transverse polarization of the acoustic surface shear waves, coolant or a heating medium can be applied to the crystal surfaces to yet further enhance the power capabilities. Alternatively, the GaAs or other piezoelectric semiconductor can also be arranged in the form of an epitaxial layer adjacent a semi-insulating substrate which would provide a form of heat sink to further enhance the output power capabilities.

While the operation of the arrangement with acoustic surface shear waves is preferred for the reasons enumerated hereinabove and to be discussed in more detail hereinafter, it is to be understood that other acoustic waves can be utilized to advantage with an output resultant from the variation in the depletion layer adjacent the contacting output electrodes. For example, Rayleigh waves or bulk waves can be utilized to provide a useful arrangement. Furthermore, in the convolution operation, waves of different frequencies can be introduced to opposite ends of the piezoelectric semiconductor and the output electrode then need merely be varied to take the form of an interdigital structure tuned to the summation of the input wave frequencies. Furthermore, depending upon the character of acoustic waves, different input transducers can be utilized.

BRIEF DESCRIPTION OF THE DRAWINGS

The stated objective of the invention and the manner in which it is achieved, as summarized hereinabove, will be more readily understood from the following detailed description of the exemplary embodiments of the invention shown in the accompanying drawing wherein:

FIG. 1 is a diagrammatic perspective view of one embodiment of the invention capable of performing a convolution operation with surface shear acoustic waves,

FIG. 2 is a diagrammatic illustration of the operating principle of the FIG. 1 apparatus,

FIG. 3 is a block diagram illustrating an exemplary circuit for utilization of the FIG. 1 structure,

FIG. 4 is a diagrammatic perspective view similar to FIG. 1 of a modified arrangement utilizing Rayleigh waves, and

FIG. 5 is a partial perspective view showing a different form of input transducer for generating surface shear waves.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS OF THE INVENTION

With initial reference to FIG. 1, the illustrated apparatus embodying the invention includes a piezoelectric semiconductor 10 such as O₂ (oxygen)-doped, GaAs (gallium arsenide) which has a room temperature carrier concentration of about 2×10^{12} cm.⁻³, a resistivity of approximately 222 ohm-cm. and a Hall mobility of approximately 4,000 cm.²/V sec. As illustrated, the GaAs crystal 10 is oriented as indicated at the lower left of the figure, it being known that the [110] crystal axis is the strong acoustic wave propagation direction in this crystal.

Corresponding standard interdigital transducers 12, 14 are applied to the upper [110] surface of the crystal 10 adjacent opposite ends thereof, and in order to perform a convolution operation, pulses P₁, P₂ of radio frequency energy at identical frequencies, ω , of, for example, several hundred MHz are simultaneously applied to the two transducers 12, 14 so as to generate oppositely propagating acoustic waves in the piezoelectric semiconductor 10.

In this GaAs crystal 10 and other piezoelectric materials to be mentioned hereinafter each of the acoustic waves which are generated by the application of the radio frequency signals through the interdigital transducers 12, 14 has been found to propagate along a particular direction with only one component of particle motion which is parallel to the crystal surface and perpendicular to its sagittal plane and is generally referred to as the surface shear mode, for example, as discussed in detail in an article by J. L. Bleustein in APPLIED PHYSICS LETTERS, Vol. 13, No. 12, pages 412-413 (1968). It is thus differentiated from the more familiar Rayleigh surface wave mode which has two particle motions that are both contained in the sagittal plane as generally discussed in the October, 1972 issue of SCIENTIFIC AMERICAN, pages 51-67. Since the particle motion of the surface shear mode is parallel to the upper surface of the crystal 10, the surface characteristics of the crystal and certain other exterior environmental effects have little influence thereon, again as compared to the more common Rayleigh mode. In addition, in generally weak piezoelectric materials such as the mentioned GaAs, the surface shear wave has a relatively long penetration depth which may be as large as several hundred acoustic wave lengths as compared to the typical penetration depth of a Rayleigh wave of no more than approximately one acoustic wave length. These differentiated characteristics from bulk waves or the Rayleigh surface waves allow the use of low input power levels and have provided excellent amplification characteristics such as described in the article "Amplification of Surface Shear-Wave Mode in GaAs", by

Ludvik and Quate, in JOURNAL OF APPLIED PHYSICS, Vol. 43, No. 9, pages 3619-3622, September 1972.

In accordance with the present invention, upper and lower electrodes 16, 18 are placed across the central portion of the piezoelectric semiconductor 10 whereat the oppositely propagating acoustic surface shear waves interact, the lower electrode 18 being in the form of an ohmic contact of indium or gold while the upper electrode 16 is in the form of a thin plate or film of aluminum which forms a rectifying contact or what is generally referred to as a Schottky barrier. It may be mentioned that if the piezoelectric semiconductor 10 is of high resistivity material, the upper electrode also could be in the form of an ohmic contact. In either case the metal electrode-semiconductor contact provides a depletion layer whose width varies as a result of the electrical or space charge nonlinearity resultant from the parametric interaction of the oppositely propagating surface shear waves. More particularly, with reference to FIG. 2, when the oppositely propagating acoustic surface shear wave pulses indicated at P₁ and P₂ overlap under the metal electrode 16, the parametric interaction thereof changes the total concentration of ionized donors and traps, N_D, which in turn varies the width W of the depletion layer substantially as exemplified in the following table:

W (microns)	N _D (cm. ⁻³)
34.8	10 ¹²
3.48	10 ¹⁴
0.348	10 ¹⁶

More particularly, the parametric interaction of the two waves provides in essence a multiplication of the electric fields (requisite to a convolution operation) which varies the carrier concentration in the semiconductor 10 to change the effective carrier spacing relative to the electrode 16 thus to provide a change in capacitance.

Such depletion layer variation drives the output circuit 20 connected to the electrode 16 so that an output electromagnetic signal at twice the input frequency ω is derived. More particularly, if the input signals are identical rectangular pulses P₁, P₂ the output signal P₃ will be in the convolution form represented by a triangular waveform as indicated in FIG. 2.

It will be apparent that other piezoelectric semiconductors can be utilized, CdS, InP, InAs, and GaP being examples. For the interaction of the surface shear waves in the manner described hereinabove, higher Hall mobilities and weaker piezoelectricity are preferred. As a consequence compounds composed of elements from Group III and Group V of the Periodic Table are preferred over those compounds including elements of Groups II and VI, although both types can be successfully employed.

A detailed experimental arrangement for performing the convolution operation in accordance with the present invention is shown in block diagram in FIG. 3, wherein identical pulses P₁, P₂, at frequencies of 205 MHz are delivered through radio frequency amplifiers 22, 24 and tuners 26, 28 to the transducers 12, 14 at opposite ends of the GaAs piezoelectric semiconductor

10. Preferably, the pulse lengths are chosen so that they will interact throughout the entire region between the output electrodes 16, 18, thus to maximize the output which is then delivered from such output electrodes through a tuner 30 and mixer 32 connected to a local oscillator 34 so that an intermediate frequency signal can then be amplified and detected, in a combined amplifier-detector 36, and delivered to an oscilloscope 38 for representation of the modulation output P_3 in the triangular format mentioned hereinbefore.

As a practical matter, real-time convolution can be obtained with radio frequency signals in the range of from 0.1 to 1 GHz and the electrical or space charge nonlinearity provided by the metal-semiconductor contact allows operation at much lower acoustic power levels and with much greater efficiency than the prior convolution arrangements wherein the output was predicated upon the elastic (strain) nonlinearities.

The efficiency of the operation does vary with temperature in different semiconductors. Accordingly, as diagrammatically indicated in FIG. 3, in a conventional fashion, gas can be cooled in a liquid nitrogen heat exchanger 40 and applied to an enclosure 42 around the GaAs crystal 10 to maintain it at the desired low temperature whereat maximum output electrical power can be achieved. With other crystals, cooling or heating means can be employed to optimize the results.

In addition, the effectiveness of the arrangement can also be changed by varying the depletion layer thickness or width W in the absence of the acoustic waves very simply through the application of a bias voltage V which may be either negative or positive, depending upon the particular characteristics of the crystal being utilized.

While the electrical nonlinearities resulting from the metal-semiconductor contact can advantageously employ surface shear waves as described in detail hereinabove, other surface waves such as Rayleigh waves can be utilized in carrying out the same principle of operation. Furthermore, individual variances of the apparatus can be envisioned while utilizing the same principle of driving the output circuit as a result of the electrical or space charge nonlinearities provided by a metal-semiconductor contact. By way of example, in FIG. 4, a modified arrangement corresponding to that shown in FIG. 1 utilizes the principle of the invention by application of Rayleigh waves in epitaxial GaAs. More particularly, a layer 44 of n-type GaAs with a carrier concentration of $2 \times 10^{15} \text{ cm}^{-3}$ and thickness of approximately 4 microns was grown on a semi-insulating substrate 46 of GaAs. The layer 44 of n-type GaAs was oriented differently from the structure described in connection with FIG. 1 so that the upper surface constitutes the [001] crystal surface of the GaAs and interdigital transducers 48, 50 were formed at opposite ends of this upper surface so that the modulated radio frequency input to such transducers generated Rayleigh surface waves which propagated towards one another so as to interact under a central output electrode or plate 52 that formed a rectifying contact. Because of the different crystal orientation and the different character of the acoustic surface waves, the other electrode 54 providing for the radio frequency output signal took the form of two thin strips of ohmic material at opposite sides of the central electrode plate 52, and, as diagrammatically indicated, a suitable bias potential V can be applied thereto to vary the static condition of the de-

pletion layer, thus to optimize the output power level.

Obviously many further modifications in the operational and structural characteristics of the apparatus such as the use of bulk acoustic waves can be envisioned within the spirit of the invention with appropriate and well known input and output transducers. Additionally if the frequencies of the two waves are not equal, an output transducer of interdigital form tuned to the sum frequency so as to accommodate the spatial variation of the output signal can be utilized.

Additionally, for the generation of surface shear acoustic waves, another form of input transducer as shown in FIG. 5 can be employed and is particularly effective at higher frequencies (e.g. 1 GHz). More particularly, a longitudinal bulk wave B is excited in a ZnO thin film 60 ($\lambda/4$) between an aluminum 62 and a gold film 64 so as to initially propagate in the [001] direction in a GaAs crystal 66. The bulk wave intercepts an angular or prism face 68 at the end of the crystal so as to be converted into a surface shear wave S which is then propagated along the [110] direction. To provide such directional change, the prism angle θ is determined by

$$\tan \theta = \frac{\text{velocity (bulk wave)}}{\text{velocity (surface wave)}}$$

and is equal to approximately 54.5° in this case. For details of this arrangement, reference is made to the Lean-Shaw article in APPLIED PHYSICS LETTERS, Vol. 9, No. 10, pages 372-374 (1966).

Further modifications can be envisioned and the foregoing description of several embodiments of the invention is not to be considered in a limiting sense and the actual scope of the invention is to be indicated only by the appended claims.

What is claimed is:

1. Signal processing apparatus which comprises a piezoelectric semiconductor capable of propagating acoustic waves, transducer means for applying two electromagnetic signals to said piezoelectric semiconductor such that acoustic waves are generated therein and are translated with respect to one another during propagation so as to parametrically interact at an overlapping position in said piezoelectric semiconductor, and an output electrode forming a rectifying barrier at the surface of said piezoelectric semiconductor at the wave-overlapping position to sense variations in the depletion layer resultant from the electric fields caused by the parametric wave interaction.
2. Signal processing apparatus according to claim 1 wherein said piezoelectric semiconductor is a crystal so oriented relative to said transducer means so that the acoustic waves take the form of surface shear waves.
3. Signal processing apparatus according to claim 1 which comprises means for generating two electromagnetic signals of identical frequency and identical pulses for application to said transducer means.
4. Signal processing apparatus according to claim 1 which comprises means for applying a predetermined DC bias voltage to said output electrode.
5. Signal processing apparatus according to claim 1 which comprises means for varying the temperature of said piezoelectric semiconductor.

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