536. Piezo - and pyroelectric GaAs sensors integrated in one crystal with GaAs FET

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Abstract. One of important problems of recent electronics is non-cooled pyroelectric and piezoelectric sensors. They are realized usually in a hybrid integrated chip where thousands of ferroelectric ceramic elements are integrated with transistor matrix. Reported research work is devoted to the possibility of realization of one-crystal pyroelectric sensor. We revealed new effect of symmetry decrease that is used as a basis to develop one-crystal pyroelectric or piezoelectric sensor array using III-V crystals. In feasible sensor devices, the transducer, the amplifier and read-out electronics would be the various parts of one crystal chip. Voltage sensitivity of semi-insulating GaAs-type temperature sensor is the same as one of PZT pyroelectric ceramics. However, proposed device will be fully made from GaAs and related crystal layers by the standard in the micro-electronics technology.

Keywords: gallium arsenide, piezoelectric, pyroelectric, membrane, FET.

1. Introduction

In the last couple of years the ferroelectric, pyroelectric and piezoelectric devices have attracted a lot of attention due to their applications in the electronics, machinery and equipment industries and overall substantial progress made in the microelectrics technology and technological advancement of micromechanical devices. These materials are of great significance taking the leading role in the development of sensors, actuators, optical and automatic devices, mechatronic systems, telecommunication equipment and others. These dielectric devices are often called „smart materials". They will be of great importance looking forward in the realization of high-precision mechanisms that are based on micromachining science.

Active dielectrics could be identified as material medium, which allows to obtain direct transformation of energy and information. For example, piezoelectric devices transform active (electrical) energy into mechanical energy and vice versa. Pyroelectric devices transform heat energy. This transformation ability is due to crystallized structure and chemical composition of some materials, mainly dielectrics.

The classification of physical effects in dielectrics is presented in Table 1.

Effects indicated on the diagonal line are observed in the active and common electroisolation materials. For example, when material is influenced by the electric field, the following can be observed:

- polarization of dielectrics and electric current, which is described as conductivity;
- on the second line magnetization occurs because of the generation of the magnetic field, which is described as permeability;
- on the third line, deformation occurs as response to stresses via elasticity due to mechanical tension, etc.

Table 1. Classification of physical effects in dielectrics

Action / Response	Dielectrics	Magnetics	Mechanical	Heat exchange	Transformation optical properties
Electrical field	Polarization, electric current	Electro-magnetic effect	Backward piezoeffect	Electrocaloric effect	Electro-optical effect
Magnetic field	Magneto-electrical effect	Magnetization	Magnetostriction	Magnetocaloric effect	Magneto-optical effect
Mechanical tension	Direct piezoeffect	Piezomagnetic effect	Deformation	Elastoheating effect	Photoelastic effect
Heat transformation	Pyroelectric effect	Thermomagnetic effect	Thermal	Thermocontent	Thermooptical effect
Light	Photovoltage effect	Photomagnetic effect	Photostriction	Light absorbtion	Refraction and reflection of light

Active dielectrics have notable characteristics called crossing effects. For example, in the first column of the table, mechanical tension drives the following electrical responses - piezoelectric effect and heat summon pyroelectric effect, while light drives photovoltage effects. As Table 1 demonstrates, plenty of such effects can be observed. The application of ferroelectric devices has spread widely in the last few years. The application of active dielectrics could be divided into three groups:

- thin ferroelectric films, monolithically connected with semiconductors;
- microsystems which include sensors, actuators, processors;
- the components characterized by super high frequency that are based on active dielectrics.

2. Research topics

Physical background. Charge separation phenomena in dielectrics have always been associated with the change of spontaneous polarization under the scalar (thermal or mechanical) influence. It was assumed previously that these properties are related to the crystals of 10 pyroelectric classes only. This work will demonstrate that scalar thermal influence may induce pyroelectricity in the other 10 "true piezoelectric" classes of polar crystals, and the most important application of this effect is expected in the III-V semiconductors-piezoelectrics [1]. In a more wide sense, our work proves that mechanical conditions affect polar crystal lattice symmetry and its electric response to external influences.

Under the anisotropy of boundary conditions, any high-gap III-V semiconductor indicates a behavior of pyroelectric crystal (despite that it is a piezoelectric only) [2]. Partial strain limitation makes it possible to obtain in the {111}-planes of these crystals a strong electric response on scalar external influence such as hydrodynamic pressure or change of temperature (Fig. 1).

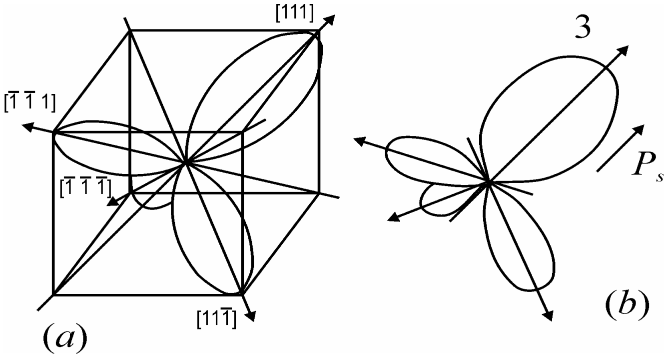

Fig. 1. Piezoelectric modulus distribution in GaAs: *a* – polar-neutral structure in a stressed-free crystal; *b* – analogous of spontaneous polarization that appears under partial stress induced thermally [3]

Basic technology. Pyroelectric or piezoelectric response can be obtained in the finned design of GaAs substrate. Very high resistive (nearly a dielectric) AlGaAs layer should be deposited previously on the {111} GaAs wafer by the liquid phase epitaxial process. After the etching, this layer will form the piezoelectric membranes [4]. Thin epitaxial GaAs film (which is the basis of a FET type amplifier) is located onto the membrane, which operates as “piezo-electric gate” (Fig. 2). Using mask and etching technique, the cavities could be created in the basis plate forming the membranes, which plane strain is limited by the thick edges [5]. Thin and “soft” membranes separated by thick and “hard” edges provide a way to obtain the artificial pyroelectric effect as well as the volumetric piezoelectric effect. Experiments indicate that such membrane-type structure provides electric response of 2-4 times larger than thin-plate soldered on rigid substrate.

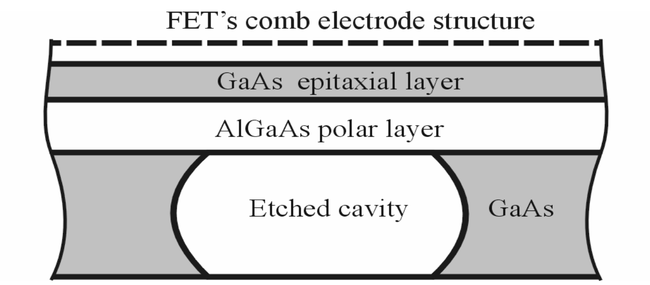

Fig. 2. Simplified model of GaAs–based pyroelectric (or piezoelectric) transistor. Pyroelectric or piezoelectric response can be obtained in the finned design of GaAs substrate. Very high resistive (nearly a dielectric) AlGaAs layer will be deposited previously on the [111] GaAs wafer by the liquid phase epitaxial process. After the etching, this layer will form the piezoelectric membranes. Infrared illumination falls from etched cavity

Thin and “soft” membranes separated by thick and “hard” edges provide a way to obtain the artificial pyroelectric effect as well as the volumetric piezoelectric effect [5-6]. Being heated by the IR illumination (or being compressed by the change of external pressure), the membrane generates electric potential to control field-effect transistor. Thus, a membrane is used in the FET instead of the gate. A new device is named “pyroelectric transistor”, and consists of the membrane-transducer integrated with the FET amplifier in the one-crystal structure. “Pyro-transistor” needs a cavity covered from inside by the infrared absorbent layer, while in the case of “piezo-transistor” the etched cavity should be closed [8]. These devices can be widely used in the various electronic systems of thermal or pressure control.

This research work opens up the possibilities for a new type of microelectronic sensor that would be non-cooling one-crystal sensor. Being fabricated by the microelectronics technology, one-crystal GaAs based sensors would have a low cost as for single-element sensor, so in the case of several sensor-cells joint in a matrix [7]. Finned structure can be realized by micromachining, and it is worth to note that sensitivity of thermal image processor increases as square root of cell number (the identity of each cell of such array is feasible using microelectronics). New type sensor would have advantages over semiconductor photon arrays that need cooling and over pyroelectric ones produced by hybrid processing.

This research work is devoted to a new feasibility to realize *one-crystal* pyroelectric & piezoelectric sensor. With this aim in mind, the only one class of crystals is possible to use, namely, the III-V crystals that are semiconductors-piezoelectrics, and to start with the well-elaborated GaAs. The etching of these crystals will not cause problems, and they do not need very big bias field [9]. Instead of electric bias, piezoelectric crystal needs a sort of “mechanical bias” to decrease the symmetry of its response. However, in future IR device, the sensor cell will not be stressed continuously. The special boundary conditions are used in the cell that only limits one type of deformations (usually a plane strain) [10]. Due to this limitation, the measured influence produces in the element some stress even though very small. Thus, on the contrary to sensor elements made from ceramics (which need a strong electric bias field) no drastic external forcing is required for piezoelectric based sensor array. Therefore, this work proposes to use artificially-arranged polar response in a piezoelectric, namely, in semi-insulating (practically dielectric) high-gap III-V semiconductor.

Advantages of new devices. Presented research project is aimed at realization of one-crystal pyroelectric-like sensor. In the proposed sensor devices, the transducer, the amplifier, and read-out electronics would be the various parts of one crystal chip.

Non-cooled pyroelectric sensor is one of important problems of recent electronics. However, it is realized in the *hybrid microelectronics* when thousands of ferroelectric ceramic elements are integrated with the transistor matrix [11]. Constituent hybrid structure faces problems because their components have fairly different chemical and physical properties.

In the IR arrays, ferroelectric or paraelectric ceramics are usually used because ferroelectric crystals cannot provide homogeneity of each sensor cell in the matrix. Ferroelectric ceramics have a random orientation of their domains. To be used as sensor, these ceramics needs to be “polarized” by the external electric field, which arranges preferential “single domain” structure. IR image arrays might use paraelectric ceramics or diffuse phase transition ferroelectric ceramics with $\boldsymbol{\varepsilon} > 10^4$ in which sensitivity increases as $\boldsymbol{\varepsilon}^2$ [12]. In this case, the internal polarization of high-$\boldsymbol{\varepsilon}$ paraelectric ceramics should be induced and supported by the external electric bias field as well [13].

Based on any ceramics, IR image structures have some disadvantages. Firstly, to induce pyroelectric properties in non-polar ceramics, a strong external electric bias field must be applied to the element pitch. As a result, there is possibility of electrically-stimulated aging and electrochemical breakdown of thin ceramic elements [14]. The second problem is the difficulties in etching of ceramics that have a polycrystalline (grain) structure, while the speed of etching is different for the grains and for layers between them. Therefore wet etching can destroy ceramics.

3. Conclusions

It was established that under the anisotropy of boundary conditions, any high-gap III-V semiconductor indicates a behavior of pyroelectric crystal (despite that it is a piezoelectric only). Partial strain limitation enables achievement in the {111}-planes of these crystals a strong electric response to scalar external influence such as hydrodynamic pressure or change of temperature. New effect of symmetry reduction forms a basis to elaborate one-crystal pyroelectric or piezoelectric sensor array based on III-V crystals. Voltage sensitivity of semi-insulating GaAs-type temperature sensor is the same as one of PZT pyroelectric ceramics. The point is that III-V crystal dielectric constant is at least 50 times lower than PZT dielectric constant.

A cell of proposed sensor represents a new device named "pyroelectric transistor" that consists of III-V crystal membrane-transducer integrated with FET amplifier in the one-crystal structure. Thus the research work is based on original physical effect that makes it possible to use non-hybrid microelectronics in the production of IR and pressure sensors in one crystal array.

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