ARTIFICIAL PYROELECTRICITY IN i-GaAs AND ITS POSSIBLE APPLICATION

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Abstract. GaAs is a material exhibiting the most promise for microwave microelectronics. This work shows that polyfunctional properties of i-GaAs and other 111-V semi-insulating crystals would be expanded by the artificial decreasing of their electric response symmetry that could be transformed from the piezo- into a pyroelectric class. Generated by temperature gradient of by partial clamping "pyroelectric" field is extremely dependent on crystal orientation that must be taken into account as one of the reasons of powerful microwave devices degradation. New effect would be applied also for some MMIC filter-selector devices and as new type of "pyroelectric" sensor. The last is possible to use as small integrated pyrotransistors for very fast temperature control in the vicinity of powerful MESFET or HEMT devices and laser diodes as well.

Dielectric properties of semiconductors and partly their piezoelectric activity have usually been out of consideration because of charge carries screening effect. As a matter of fact, polar properties of GaAs-type crystals have been taken into account for charge carries mobility. It seems also that GaAs crystal latent (intrinsic) piezoelectric polarity provides the basis of Gunn effect and of strained-layer superlattice"piezoelectric HEMTs". But in this work *charge generation process* is ignored so the term *charge separation* has to be used. By this means semiconductor lattice is considered as dielectric and only electric polarization should be taken into account. This is very close to real situation in semi-insulated GaAs and all the more in its solid solutions with AlP. The goal to be sought is to transform passive i-GaAs wafer into an "active" thermal-to-electric energy transducer. It is known that only the crystals of pyroelectric symmetry is operable as such transducers while GaAs-type crystals are nothing more than piezoelectrics. Nevertheless, Fig.1-3 show how to get artificial pyroelectric response from the piezoelectric of GaAs symmetry.

Usual pyroelectricity is based on spontaneous polarization (Ps) temperature dependence, Fig.1a. It is important to keep in mind that pyroelectric coefficient γ_i includes the secondary coefficient γ''_i from the piezoelectrically transformed strains (Fig.1b) where e_{im} is piezocoefficient and α_m is thermal expansion coefficient. The symmetry requires the pyroelectric crystal to have unique polar axis which direction coincides with Ps.So only 10 from 20 piezoelectric classes of crystals allow pyroelectricity (primary and secondary).Another 10 piezoelectric classes show latent polar structure which is self-compensated if crystals are stress-free. Recently it has been originally shown that uniform thermal influence induces pyroelectric response in all 20 piezoelectric classes of crystals if they are partially clamped[1]. The nature of this unusual response is explicable: piezoelectric crystal unit cell arrangement corresponds to complex multipole structure which is totally self-compensated in a stress-free case. However, this intrinsic=latent electric polarity could be artificially decompensated.

In the case being considered the GaAs unit cell possesses an octupole-type intrinsic polarity which is totally compensated because of its four 3-fold polar axes are crossing at angle of 109.5° as shown at Fig.2a.

Sphalerite self-compensated polarity could be artificially broken due to partial limitation of strains under special boundary conditions.Therein lies to our effect which manifestation is illustrated with explanatory drawings (Fig.2b and 3c).The effect was named as *thermopiezoelectric response*,TPER[2].

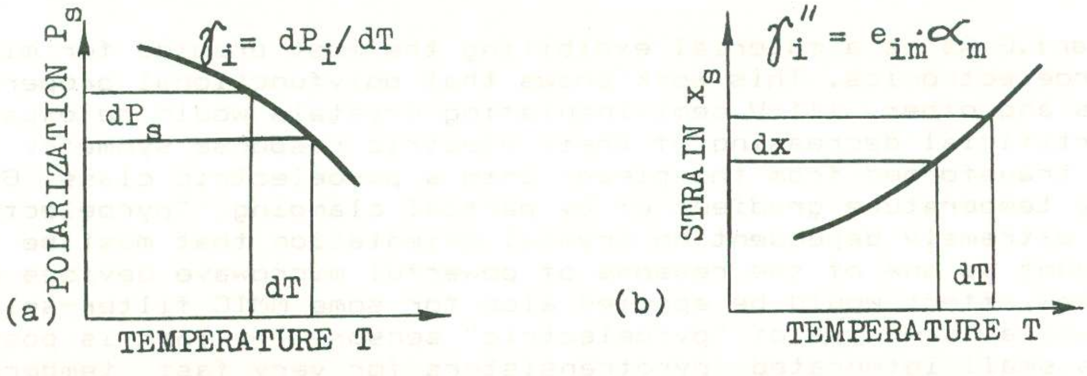

FIGURE 1 Pyroelectricity: sum response (a), secondary response (b).

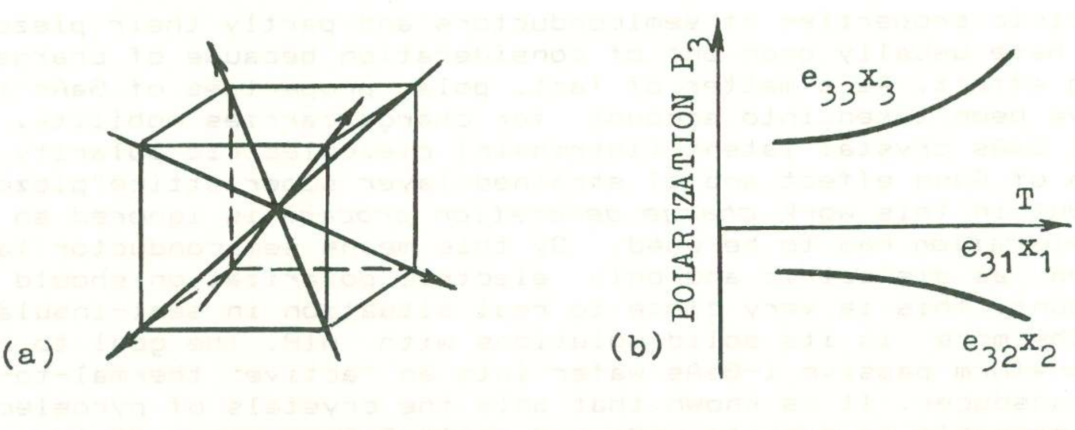

FIGURE 2 TPER in sphalerite crystal, four polar axes (a), piezoelectrically transduced thermal strains (b).

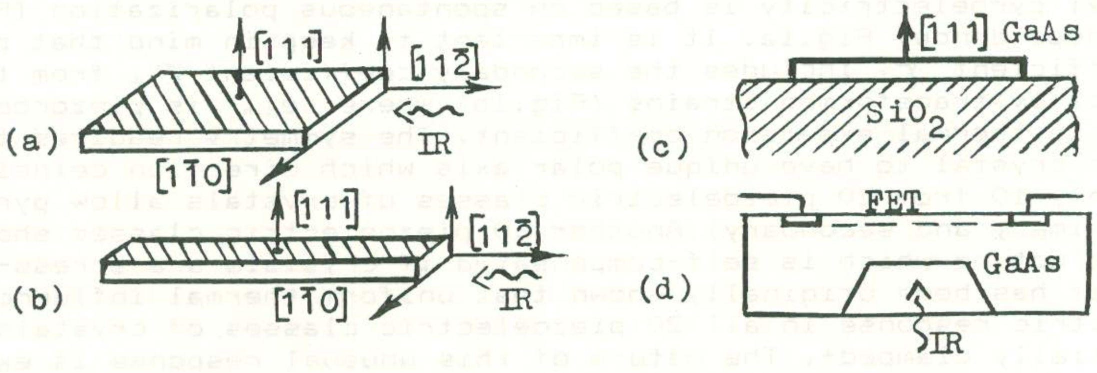

FIGURE 3 Various samples for TPER investigations: plate (a), rod (b), plate on substrate (c), complex configuration provided nonisotropic clamping (d), IR - infrared beam.

Thin crystal plate of (111)-cut shows longitudinal piezoeffect $P_3=e_{33}\ x_3$ where"3"is [111]-axis and transverse piezoeffect $P_3 = (e_{31}+e_{32})x_3$. The sum of piezoelectric coefficients $e_{31}+ e_{32}+ e_{33}= 0$ so any of scalar influence totally compensates each other if crystal is free to expand. Compensation is shown on Fig.2b for GaAs crystal thermal treatment: piezoelectric contribution from longitudinal strain component $x_3= \alpha$ dT is exactly compensated by two transverse components $x_1= x_2= \alpha$ dT. If the last ones are forbidden by planar clamping the polarization $P_3 = e_{33} \alpha$ dT imitates "pyroelectricity". By this means Fig.2b transforms into Fig.1b so the new effect is equivalent to secondary pyroelectric effect inherent in pyroelectrics but previously unknown in piezoelectrics.

Partial clamping was realized by various ways. In our first experiments the modulated beam of CO_2-laser or modulated microwave source were employed for crystal heating. In this "dynamic" method[3] piezoelectric thin plates, disks or rods were free suspended in the laser beam (Fig.3 a,b) or softly arranged in the microwave waveguide so under the modulated heat influence a "natural" electromechanic clamping was realized for the main piezoelectric crystals and for GaAs as well. It has been determined that 0.1 mm thick GaAs plate can produce voltage about 2 V/K that corresponds to "pyrocoefficient"= $\gamma = dP/dT = 1.5\cdot10^{-6}$ C/m^2K with a voltage sensitivity $S_V = 0.02\ m^2C^{-1}$. Our investigations show that some of III-V semiconductors capable to form solid solutions with GaAs have these parameters 10 times more. Above all they are much closer to dielectrics than i-GaAs.

In one of our "static" experiment[4] thin [111]-plate of semi-insulating GaAs was cemented to hard substrate with low thermal expansion coefficient, Fig.3c. This is rather convenient for providing measurements but for device special etching process application would suffice to provide planar limitation of strains,Fig.3d.The finned design of i-GaAs-type many-cells thermal-to-electric convertor reminds bee's honeycomb.Another way for planar strain limitation is to compress the transduser by rigid ring.In any case the only thermally induced thickness strain should be permitted and just in the direction of [111]-type polar axis[5].

Thus, the boundary conditions could transform the piezoelectric crystal into "pyroelectric" one. Apart from thermal sensitivity, pyroelectrics are capable to volume piezoeffect under the hydrostatic influence (stress-free "pure"piezoelectrics do not exhibit this property[6]. Techniques of producing and study volume piezoeffect in semi-insulating GaAs crystal is analogues to artificial pyroelectricity: if the volume piezoelectric effect is desired a rigid steel has to be used as a substrate. From thermal treatments we have obtained the value of octupole component of GaAs latent polarity: near 300 K $P_{[111]}= 0.2\ C/cm^2$ (equivalent intrinsic electric field is 2.10^7 V/m).

Decreasing with temperature $P_{[111]}$ produces artificial pyrocoefficient:

$$\gamma_{111} = dP/dt = 2\sqrt{3}\, d_{14}\, \alpha /(4\, S_{11} + 8S_{12} + S_{44}),$$

where d_{14} is piezoelectric constant, α is thermal expansion and S_{mn} are elastic compliances.It is evident that (111)-cut shows the maximum of effect and we calculated its angle distribution in the spherical coordinates:

$$\gamma(\theta,\varphi) = \gamma_{111} \sin 2\theta \sin\theta \sin 2\varphi$$

where θ is the angle deflection from [111]-axis and φ is azimuth. Electric field produced in the GaAs-type crystal by its partial clamping or temperature gradient is distributed in the same fashion. It has effect on the ions migration and finally on thermal and time degradation of powerful devices.

From viewpoint of specialist in materials, new effect should have some interesting applications. For example, we realized microwave filter-selector with two resonances simultaneously: a microwave one due to the i-GaAs plate is dielectric resonator tuned to the based frequency and acoustic resonance in the same plate exited by microwave modulation frequency (the last should correspond to the frequency of GaAs (111)-plate piezoelectric resonance). The practicability of two resonances would require special care[7]. When only one microwave resonance has to be realized, i-GaAs plates have to be fasten with rigid substrates. Both filters are pyroelectric detectors as well.

Another example of new effect application is the possibility to create non-photonic (and non-cooled) sensitive receiver of millimiter, submillimiter and far infrared radiation. Simple one-crystal device should be useful for field diagnostic. It can be coupled with halkogenide transmission lines such as Ge-As-Se being applied instead of photodetectors which need cooling. Integrated with FET amplifier GaAs-type artificial "pyrotransducer" can be the basis for new microelectronic device named *pyrotransistor*. The last one consists of FET integrated on i-GaAs (111)-cut wafer which is operating as "pyrogate". Hundreds of such pyrotransistors on the same wafer would form matrix thermal image processor which sensitivity increases as square root from cells number (if their properties are identical). The current status of microelectronic technology can guarantee the same properties of each cells of such one crystal processor and makes possible read-out circuits.

The main problem of known pyroelectric integrated sensors is to provide negligible thermal contact between pyroelectric transducer and high thermoconductive silicon wafer. So such devices really need complicated system of packaging. Moreover, rigid bound of several materials with a sharp distinction between chemical and thermal properties poses problems for technology. For instance, as water-soluble pyroelectric-champion TGS so the crystals of $LiTaO_3$-type are difficult to integrate with semiconductor matrix processor. Moreover, all pyroelectric cells of such hybrid-type "pyroprocessor" have different sensitivity so the effect from these matrix fall short of this ideal. But in our case the GaAs-type wafer is a "pyroelectric" transducer itself while amplifiers and other microelectronics is no more than a very thin epitaxial layers with ultra low thermal mass.

Thus, the inclusion of thermally and stress induced electric fields in semi-insulated GaAs-type wafers should give new insight into devices degradation. On the other hand, providing the possibilities for partial limitation of strains one could essentially widen polyfunctional capabilities of GaAs-type crystals.

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