EPJ Web of Conferences **41**, 04005 (2013)
DOI: 10.1051/epjconf/20134104005

Competition between inverse piezoelectric effect and deformation potential mechanism in undoped GaAs revealed by ultrafast acoustics

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Abstract. By using the picosecond ultrasonics technique, piezoelectric effect in <111> GaAs undoped sample at both faces (A[111] and B[-1-1-1]) is experimentally studied. We demonstrate that piezoelectric generation of sound can dominate in <111> GaAs material over the deformation potential mechanism even in the absence of static externally applied or built-in electric field in the semiconductor material. In that case, the Dember field, caused by the separation of photo-generated electrons and holes in the process of supersonic diffusion, is sufficient for the dominance of the piezoelectric mechanism during the optoacoustic excitation. The experimental results on the sample at both faces reveal that in one case (A face), the two mechanisms, piezoelectric effect and deformation potential, can compensate each other leading to a large decrease of the measured Brillouin oscillation magnitude.

1 Introduction

Picosecond ultrasonics [1] is a technique which permits to carry on contactless and non-destructive investigation of the elasticity of different kinds of materials and structures at nanoscales [2-4]. From a more fundamental point of view, this method also offers the possibility to investigate at ultrashort time scales electron-hole-acoustic phonons coupling mechanisms [1,5-8]. Recently it has been experimentally reported that hypersound generation by laser-induced inverse piezoelectric effect could be more efficient than generation via deformation potential mechanism [6-9]. In previous works [8], we demonstrated that the transient electric fields, necessary for the piezoelectric optoacoustic transformation, can be induced by the separation of the photo-generated electrons and holes in pre-existing residual electric fields (surface or interface built-in field [7-9]). We present here new experimental results and analysis of the generation efficiency of inverse piezoelectric effect driven by Dember field versus deformation potential in non-doped <111> GaAs.

2 Principle of experiments

The Figure 1a presents the experimental set-up.
The principle of the experiment is to generate an acoustic pulse in the studied material using a 400 nm pump beam and to detect it with a 800 nm probe beam (pump-probe scheme). The pump beam radiation penetrates locally in GaAs wafer with a typical penetration depth of 20 nm.

Photogenerated coherent acoustic phonons propagate then inside the single crystal. These phonons are detected with the deeply (800 nm [13]) penetrating probe radiation. The probe photon is scattered by acoustic phonons and due to momentum conservation, only one acoustic mode is detected (time resolved detected Brillouin mode is illustrated in Fig. 1b, 1c [1,7]). Moreover, a technical originality is added to this set-up by the use of a spinning wedge mirror which allows to implement experiments avoiding damages due to thermal and curing effects at the sample surface.
We have then analysed the magnitude and the phase of Brillouin oscillations for different pump fluences for both faces A[111] and B[-1-1-1] having opposite piezoelectric coupling constants [11]. Our samples are non-doped (Resistivity>10^7ohm.cm) leading to a very weak built-in electric field that always exists in the vicinity of the semiconductor surface (less than 100V/m [10,11]).

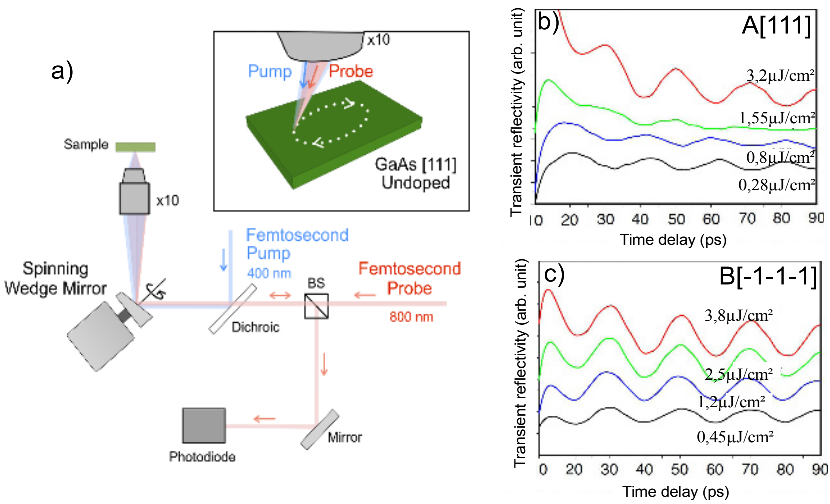

Fig. 1. Experimental scheme (a) and transient reflectivity signals at different pump fluences obtained for both faces of the samples: Face A [111] (b) and face B [-1-1-1] (c).

3 Results and analysis

The Brillouin signal analysis shows clear difference between generation processes involved for A[111] and B[-1-1-1] orientations. This magnitude increases with pump fluence for face B[-1-1-1] (Fig. 1c and 2a), while there is a given pump fluence close to 1,55 μJ/cm² where it nearly vanishes for face A[111] (Fig. 1b and 2a). This peculiarity also appears in the phase analysis with an abrupt phase jump for face A. The linear trend at high fluence is known to be the signature of coherent acoustic phonon generation process according to the deformation potential. In this particular case, it is known that the photoinduced stress due to the deformation potential gives rise to a compressional acoustic wave whatever the orientation of the crystal (i.e. A[111] or B[-1-1-1])
On the contrary, a non-linear trend in the amplitude evolution with the pump fluence is observed at low fluences and the Brillouin phase exhibits a π shift between the two crystallographic orientations (Fig. 1b, 1c and 2b). The fact that the Brillouin oscillations magnitude (which is proportional to the photoinduced acoustic field) vanishes for face A[111] and not for face B[-1-1-1] shows that a competition between acoustic phonons emission processes exists for the orientation [111]. We can straightforwardly rule out the contribution from the inverse piezoelectric effect coming from the photo-screening of the pre-existing electric field since this field, as mentioned in part 2, is smaller than 100 V/m [10]. As a consequence, the only process we claim to be possible to explain the pump dependence of the Brillouin magnitude and the phase, is the inverse piezoelectric effect driven by the Dember electric field. The Dember field rises during the sudden separation of the photogenerated electrons and holes in the process of their supersonic motion at femtosecond-picosecond time scales

[10]. The maximum magnitude of the Dember field is [10] $E_{Dember} \sim (kT\alpha)/e \sim 10^6$ V/m (where k, α and e are the Boltzman constant, the absorption coefficient of pump radiation at 400 nm and the elementary charge). Therefore, with a piezoelectric constant p_E of around 0.1 C/m² [11], this leads to inverse piezoelectric effect mechanical stress inverse of the order of 10^5 Pa ($+10^5$ Pa for face A[111] and -10^5 Pa for face B[-1-1-1]). Furthermore, the deformation potential can be estimated as [5,10]: $\sigma_{eh}=-N.dE_g/dP.B \sim -5.10^5$ Pa, where $N\sim10^{23}m^{-3}$ (for a pump fluence of 0.5microJ/cm^2), $dE_g/dP=9.10^{-11}$ eV/Pa [11] and $B=7.5.10^{10}$ Pa [11] are respectively the concentrations of carriers that are optically excited by the pump, the deformation potential constant and the bulk modulus. These estimates show that these stresses have comparable magnitude but have opposite sign for face A[111]. As a consequence, for this face, deformation and piezoelectric effects compete as illustrated by the vanishing Brillouin oscillations (Fig 1b and 1c). In order to obtain more detailed microscopic mechanism of this competition, it is necessary to develop now a complete model to quantify this photoinduced Dember field.

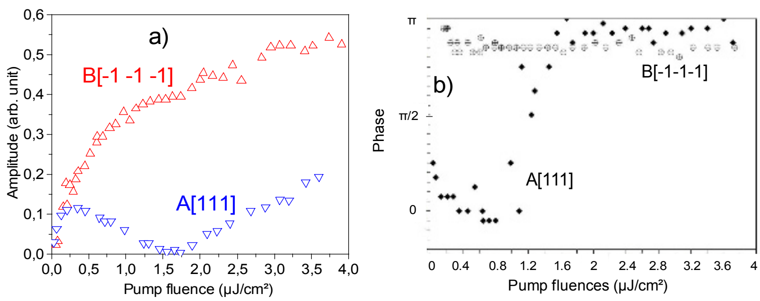

Fig. 2. Brillouin oscillations analysis versus the increasing pump fluence for each face of the sample a) Amplitudes of the oscillations; b) Phases

Conclusion

We have reported here in that the piezoelectric effect (photoinduced Dember field) in non-doped GaAs <111> semiconductor is as strong as the mechanism of electron-hole-phonon deformation potential during the optoacoustic transformation process.

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