Amplification of Surface Acoustic Waves in Graphene Film under DC-Voltage

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ABSTRACT

Using a high-resolution X-Ray diffraction measurement method, the SAW propagation process in a graphene film on the surface of a $Ca_3TaGa_3Si_2O_{14}$ (CTGS) piezoelectric crystal was investigated, where a bias potential was applied to the graphene film. It was shown for the first time that the application of the bias potential to the graphene film leads to a significant enhancement of the SAW magnitude and, as a result, to amplification of the diffraction satellites on the rocking curves. Amplification of 1 dB for the satellite +1 and 2.6 dB for satellite +2 at 471 MHz and +8V has been observed. The gain of 3.8 dB has been obtained at 471 MHz and +10 V.

Keywords: amplification of surface acoustic wave, $Ca_3TaGa_3Si_2O_{14}$ (CTGS), graphene, nikel film

1 INTRODUCTION

Nowadays, the development of acoustic-electronics based on surface and bulk acoustic waves is determined by the use of new piezoelectric materials and by the possibility of controlling the processes of propagation of acoustic waves in crystals.

The types of control of the processes of acoustic wave propagation in solid states can either be passive or active. The passive control of acoustic wave processes can be realized by fabrication of thin film coatings on crystal surfaces having certain thickness and shapes that would reduce the speed of SAW propagation. This can also be done by fabrication of reflecting metallic and profiled gratings on the crystal surface. Similarly, this can be realized by using domain structures for controlling acoustic waves in ferroelectric and ferroelastic crystals, where the domain walls can be used as acoustic waveguides and reflection structures [1-3].

Otherwise, there exists an active control of the propagation process of acoustic waves in crystals. The main way of doing active control of wave propagation is applying an electric field to a piezoelectric crystal, thus changing the piezoelectric properties of the crystals typically used for acoustic-electronics.

In Ref. [4], generation of an acoustic-electric current was observed in a graphene film transferred to the surface of a lithium-niobate crystal allowing its direct integration with interdigital transducers (IDT) used for SAW generation where the acoustically induced current scaled linearly with the input SAW power.

The goal of the present paper is the study of feasibility of controlling the process of propagation of SAWs in the crystals of the lanthanum-gallium silicate group, where the external electric field bias is applied to a few-layer graphene (FLG) film, which was deposited on a piezoelectric surface between two IDTs. This work shows a real opportunity of a direct synthesis of graphene films on the surface of crystals of the lanthanum-gallium silicate group using a gas-phase epitaxy method from ethanol vapors [5].

2 SAW DEVICE

Most of the progress in the development of the acoustic-electronics applications was based on traditional piezo-electric materials such as quartz, CdS, PZT, $LiNiO_3$ [6-16].

A SAW delay line discussed in a previous paper [17] was used as a subject of the present investigation. A five-component crystal of lanthanum-gallium silicate family $Ca_3TaGa_3Si_2O_{14}$ (CTGS) crystal grown by the Czochralski method was used as piezoelectric material grown by the Czochralski method along the {110} crystallographic axis.

Lately, main progress in the development of acoustic-electronics was related with the use of the prospective CTGS crystals belonging to the lanthanum gallium silicate (LGS or langasite) group. These crystals have a space symmetry group 32, similar to that of piezo-quartz SiO2. Unlike the SiO2 crystals, the crystals of the lanthanum gallium silicate group do not experience phase transitions up until a melting temperature of ~1500 ºC and have significantly higher values for the coefficients of electric-mechanics coupling. Low speed of SAWs in such crystals allows fabrication of miniature acoustic-electric devices.

Substrates for the experiment were fabricated by making a *Y*-cut (parallel to the (110) plane of the crystal) of the crystal, having the size of $0.5\times 8\times 16$ mm^3. Two IDTs were fabricated on the substrate surface for generation of SAW, with a wave length of Λ = 6 mm, using an electron beam lithography. SAW propagates along the X axis in a Y-cut of CTGS with the velocity of $V = 2826$ m/s. SAW propagation in a piezo-electric substrate CTGS lead to a sinusoidal modulation of the crystal lattice and to formation of the a voltage difference between the minimums and maximums of the acoustic waves due to the piezo-electric effect.

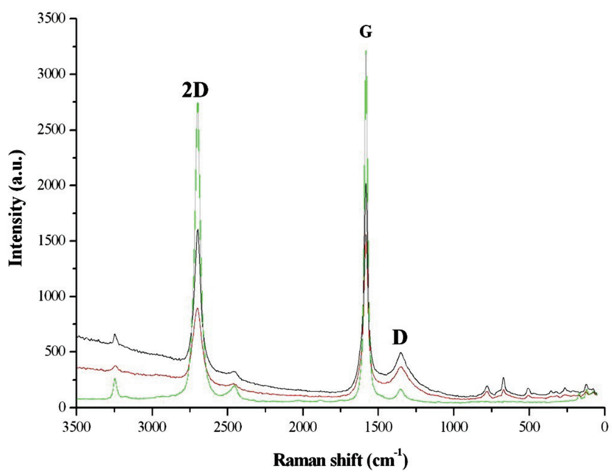

Fig.1. Raman spectra of graphene on a CTGS substrate. Different colors correspond to different spots on the substrate.

A graphene film was synthesized in an area between two IDTs on a CTGS crystal surface, where a gas-phase method of synthesis from ethyl alcohol was used.

Fig. 1 shows the Raman spectra of the graphene film fabricated on a CTGS crystal surface with characteristic G-, D-, and 2D-picks for different surface spots on the surface shown by different colors.

Three Al electrodes were fabricated on the top graphene surface by electron beam lithography, with a width of 10 μm and the distances of 300 μm, for application of the bias potential according to the schematically shown in Fig.2.

Since the graphene film has an electric resistivity of ~3 KΩ/□, applying a bias voltage to the electrodes allows creating a bias potential on graphene film and, hence, introducing control to the SAW propagation process. The bias potential applied to the graphene film, influences the electric potentials of the minima and maxima of SAW and, as a result, modifies the magnitude of SAW. It is worth mentioning that the SAW propagation process must depend on both the magnitude and the polarity of the bias potential.

3 EXPERIMENTAL SETUP

Present studies on the possibility of controlling surface acoustic waves with the bias potential which is applied to a graphene film were conducted by using a three-crystal X-Ray diffractometer schematically shown in Fig. 3.

The measurements were carried out using a 4-Bounce Bruker D8 Discover X-Ray diffractometer. X-rays were collimated by an input slit with the width of 100 μm. An X-Ray tube with a rotating copper anode (radiation $CuK_{\alpha 1}$, the wavelength was $\lambda = 1.54$ Å). As a double-crystal monochromator, Ge (220) crystals were used with dual reflection. After passing the monochromator, the X-Ray radiation encounters at the Bragg's angle with a *Y*-cut of the CTGS crystal, modulated by SAW with a wavelength of $\Lambda = 6$ μm.

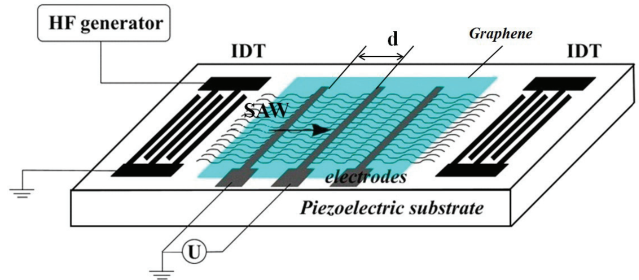

Figure 2. SAW delay time line

After the acoustically modulated crystal surface, the X-Rays fall to the analyzing crystal and then registered with a standard NaI scintillation detector. The presence of the sinusoidal modulation of crystal lattice triggers generation of diffraction satellites on the rocking curves, on both sides of the central Bragg's peak. The angular divergence between the diffraction satellites on the rocking curve is determined as:

$$\delta\Theta = d/\Lambda, \tag{1}$$

Where d is the distance between the atomic planes, and L – the wave length of SAW.

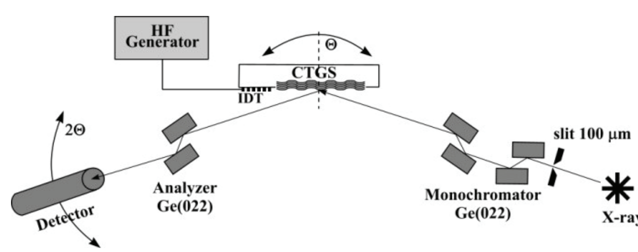

Figure 3. Experimental set-up.

4 EXPERIMENTAL RESULTS

The rocking curves of an acoustically modulated CTGS crystal were measured in order to study the effect of application of the bias potential on the graphene film placed on the top of a piezoelectric crystal during the process of SAW propagation.

Fig. 4 represents the rocking curves of a CTGS crystal measured with and without generation of SAWs on the crystal surface. The resonant frequency of SAW with the wavelength of $\Lambda = 6$ μm is $f = 471$ MHz, which corresponds to the speed of SAW propagation along the X axis of $V = \Lambda \times f = 471 \times 6 = 2826$ m/s. To generate the SAW, a high-frequency AC voltage with the amplitude of 15 V was applied to the input IDT. Excitation of SAWs in the CTGS crystal modulates the crystal lattice at the surface and, as a result, generates the diffraction satellites on the rocking curves.

If the input signal in applied to the IDT, four diffraction satellites will be located on each side around the central Bragg's peak ($m = 0$). The angular divergence between the diffraction satellites is $\delta\Theta = 0.003°$, which agrees with the value calculated with eq. (1). Fig. 4 shows that the value of the bias potential U, applied to graphene, does not make any changes to the speed of the SAWs as well as to the SAW wave length, since the angular divergence between the diffraction satellites is constant. However, it should be noted that the applied bias potential affects the intensities of the diffraction satellites, i.e. influences the magnitude of SAW. Application of the bias U=+8V increases the intensity of the satellites and reduces that of the central peak ($m = 0$) of diffraction, which is caused by the increase of the magnitude of SAW.

Application of a negative potential U = - 8V to the graphene film leads to an increase of the intensity of the zeroes Bragg's peak and to a decrease of the intensity of the diffraction satellites, which is determined by the decrease of SAW magnitude.

Therefore, application of the bias potential to a graphene film placed on top of a piezoelectric CTGS crystal allows one to change the magnitude of SAW. This effect can be explained due to a local change of crystal piezo-electric moduli in areas of the application of the bias potential.

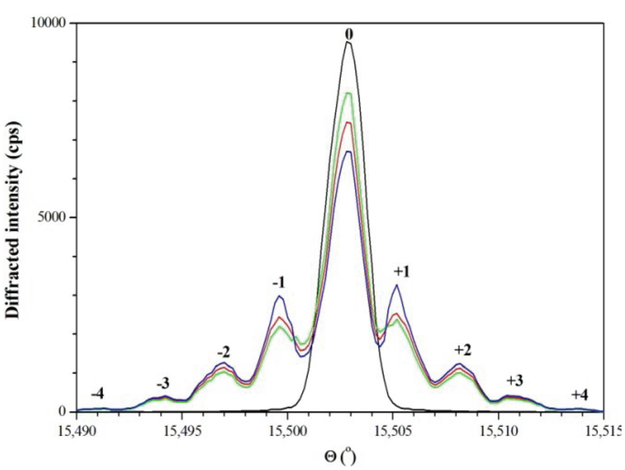

Fig. 4. Rocking curves of acoustically modulated $Y-$cut of a CTGS crystal, $\Lambda = 6$ μm: black line corresponds rocking curve without SAW excitation; red line – SAW excitation at potential $U = 0$ V supplied to graphene; blue line – SAW excitation at potential $U = +8$ V supplied to graphene; green line – SAW excitation at potential $U = -8$ V supplied to graphene.

5 DISCUSSION AND CONCLUSION

If SAW propagates on the surface of a semi-infinite piezo-electric body coated with a conducting film, or a semiconducting film is placed on the top of a piezoelectric, the surface acoustic wave on the piezo-electric attenuates due to induction of an acoustoelectric current in the conducting film by an electric field that accompanies the SAW [4].

However, if the electric current is induced in the conductive film by an external DC or AC source, the SAW in the piezoelectric can be amplified, due to generation of phonons by the electric current carriers (electrons or holes) reaching a supersonic speed in the film. Such motion of the carriers generates Cherenkov type phonons thus amplifying the acoustic wave [6-16].

This amplification effect has been studied theoretically in [6,8,9] and observed experimentally in the following piezo-electric materials: CdS [7,10,11,15], PZT [12,14], $LiNiO_3$ [13]. The electric current was produced by a DC electric field of the direction of surface acoustic wave propagation. The gain was reported to be of 18 dB at 15 MHz and 38 dB at 45 MHz in CdS, 7 dB at 107 MHz in $LiNiO_3$, and 40 dB at 4 MHz in PZT.

Our preliminary results show that application of a DC potential to the graphene film generates gain of 1-3 dB, depending on the voltage applied to the graphene film.

A feasibility of controlling the SAW propagation process caused by applying a bias potential applied to a graphene film placed on the top of a CTGS piezo-electric crystal was studied in this article. Application of the bias potential allows to change a magnitude of SAW. It should be pointed out that the graphene film is very light and, therefore, does not influence the SAW propagation process.

It should also emphasize the possibility of a direct synthesis of graphene films on the CTGS crystal substrates using the method of gas-phase synthesis from the ethyl alcohol vapor.

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