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A Transient Grating Method to Measure the Dispersion of Elastic Waves in Nanostructures

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Abstract: We describe the so-called “*Transient Grating Method*” which is a non-invasive experimental technique well suited to measure the dispersion properties of ordered or disordered nanostructures and thin films, at frequencies up to a few GHz. This pump-and-probe technique involves the interference pattern produced by two incoming IR optical pulses to set a standing elastic wave on the surface of the sample through photoelastic processes. The wave vector of this elastic wave can be easily tuned by adjusting the angle between the two incident beams. Two continuous visible laser beams in a heterodyne detection scheme are used to detect the vibrations on the surface and in turn the dispersion of the related elastic modes. The achievements of the technique are illustrated by the measurement of the dispersion of surface acoustic waves in piezogenerators consisting of GaN nanowires embedded into a dielectric matrix (HSQ). We then report on the analysis of the experimental data that allowed extracting the elastic parameters of this composite medium.

1. Introduction

Two-dimensional elastic nanostructures are found in countless industrial products and, with the progresses made in the nano/micro-fabrication techniques, devices featuring mechanical working frequencies of several hundreds of MHz are nowadays almost banal. However, experimental techniques well suited to measure the sound velocity in these systems, and in turn the dispersion, are not that many. When the device includes piezoelectric elements or electromechanical transducers, network analyzers can be used for characterization but with the disadvantage of a poor tuning of the frequency. The non-contact technique that we describe here, namely the Transient Grating Method (TGM), allows for characterizing the elastic properties of almost any kind of materials, transparent or opaque, ordered or disordered, piezoelectric or not... in a frequency range that stretches from a few tens of MHz up to several GHz.

In this work, we used this technique to investigate the features of waves guided in a fully functional piezogenerator based on GaN nanowires (NWs) embedded into a dielectric matrix [hydrogen silsesquioxane (HSQ)]. The nitride nanowires are studied for their remarkable piezoelectric properties which are very suitable for novel ultra-compact and efficient piezoelectric generators. The electric



output of a single piezoelectric NW depends on the law describing its deformation in response to a mechanical loading. However, there is still a lack of accurate understanding of the deformation and subsequent piezo-generation in such structures. Therefore, a study of such a law is highly desirable. The NWs are normally used in the form of arrays embedded in a host polymer, and the shape of their deformation is evaluated by the elastic properties of the polymer-NW composite.

2. Experimental setup and samples

Basically, the TGM¹⁻³ is a four waves mixing technique which consists in exciting the sample into vibration by illuminating its surface with two IR light pulses ($\lambda_{exc}=1064\text{nm}$; 30ps in duration). As a result, interference fringes with a period of Λ are set on the surface and standing elastic waves with a wavelength of Λ are thus created through photoelastic processes within the illuminated area. The wavelength Λ can be easily tuned by adjusting the angle between the two incident beams (see Fig. 1). From a dynamic viewpoint, several elastic modes, each fulfilling the mechanical boundary conditions and featuring the wave vector $k=2\pi/\Lambda$, may be excited by the pump pulses. Correlatively, the spectrum may feature several components at angular frequencies $\Omega^{1..n}$, where n is the number of elastic modes actually excited.

The detection of the elastic waves is made using a heterodyne scheme. This involves two continuous laser beams (respectively the probe and the reference beams) both incident on the sample with an optical angular frequency ω . The probe beam gets diffracted upon reflection on the sample, giving rise to diffraction orders ± 1 at optical angular frequencies $\omega \pm \Omega^{1..n}$. The beam at $\omega + \Omega^{1..n}$ is further mixed with the specularly reflected reference beam, whereas the beam at $\omega - \Omega^{1..n}$ is ignored. One can show that a signal with components proportional to $\cos(\Omega^{1..n} t)$ results from the mixing of both first order diffracted probe beam and specularly reflected reference beam. This signal is recorded with a fast photodiode connected to a broadband oscilloscope and further processed using conventional FFT techniques. A typical temporal signal recorded on a phononic structure with $n=4$ is shown in the right panel in Fig. 1. It is interesting to note that the elastic contribution superimposes to a slowly varying background corresponding to the cooling of the sample.

The elastic properties (Young's modulus, Poisson's ratio, and elastic constants) of a composite material (GaN NWs embedded in a HSQ layer) can then be extracted by recording the elastic modes for different k vectors at the device surface and analyzing the corresponding dispersion curves.

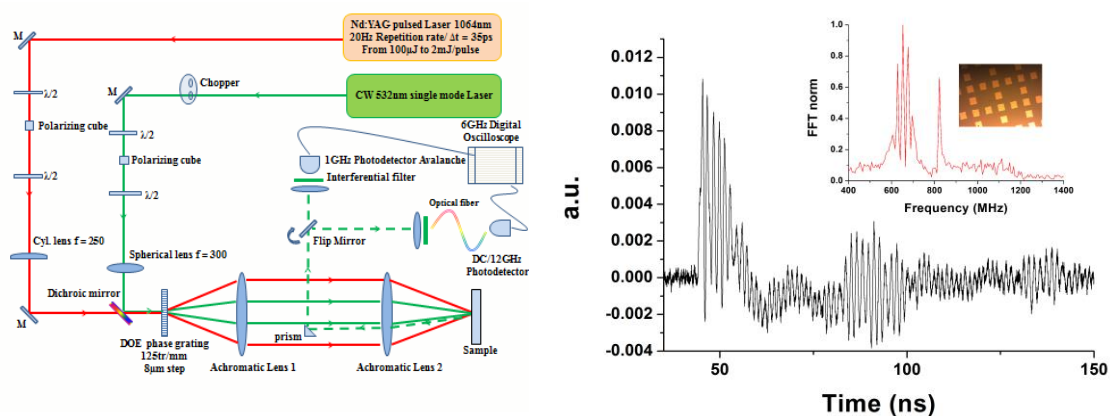


Fig.1: Scheme of the experimental setup (left panel) and typical temporal signal recorded obtained from a phononic crystal, made of Ni pillars, 400nm high and 50µm period, on a silicon substrate. This signal includes fast SAW oscillations of wavelength $\Lambda=6.2\mu\text{m}$ (right panel).

We show in the left panel in Figure 2 a MEB image of a typical sample before spin-coating process (i.e. before deposition of the polymer). The GaN NWs were vertically grown by Plasma-Assisted Molecule Beam Epitaxy. Vertical NWs with the growth direction aligned with [000-1] crystallographic axis of GaN are formed on an n-doped Si (111) substrate 260 μm thick. The NWs have an average height of 1 μm , an average diameter of 50nm with very low dispersion around this value, and a density of 10NWs/ μm^2 . A HSQ polymer was further spin-coated onto the NWs.

3. Results and discussion

We show in Fig. 2 (middle panel) the spectrum derived from the experimental signal recorded on the GaN NWs/HSQ sample and displayed in the inset.

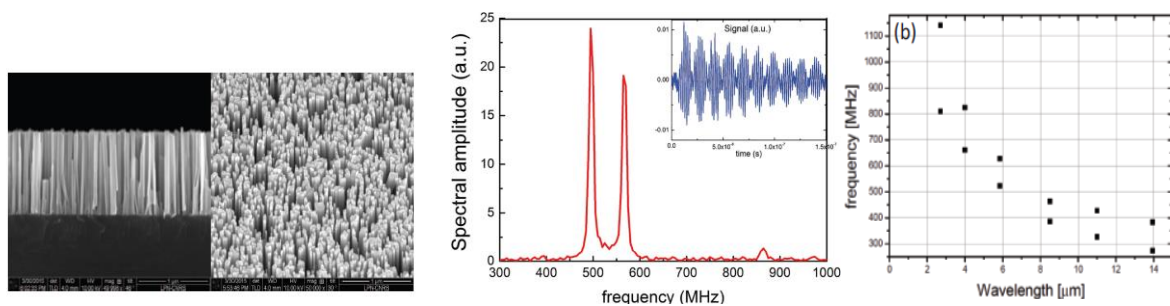


Fig.2: Left panel: MEB image of GaN NWs on n-doped Si(111) substrate. Center panel: Typical frequency spectrum of the laser-generated signal shown in the insert TGM acquired for the SAW wavelength $\Lambda = 5.85\mu\text{m}$. Right panel: Experimental dispersion curves.

The frequency spectrum features two peaks at 495 and 575MHz respectively, and a smaller one at $f=854\text{MHz}$. They correspond to the first three Rayleigh modes (the higher order Rayleigh modes are sometimes called Sezawa modes). The dispersion curves are obtained by tuning Λ owing to a proper choice of the angle between the two incident optical pulses.

In order to derive the elastic properties of the layer from the experimental data, we used an integral transform technique which, combined with the Green's matrix approach, yields explicit integral and asymptotic representations for the elastic fields generated in anisotropic multilayered structures by a given surface load [5,6]. The best fit to the experimental data was obtained by minimizing the goal function, which specifies their deviation, by varying the five independent elastic moduli C_{ij} and the density of the composite medium.

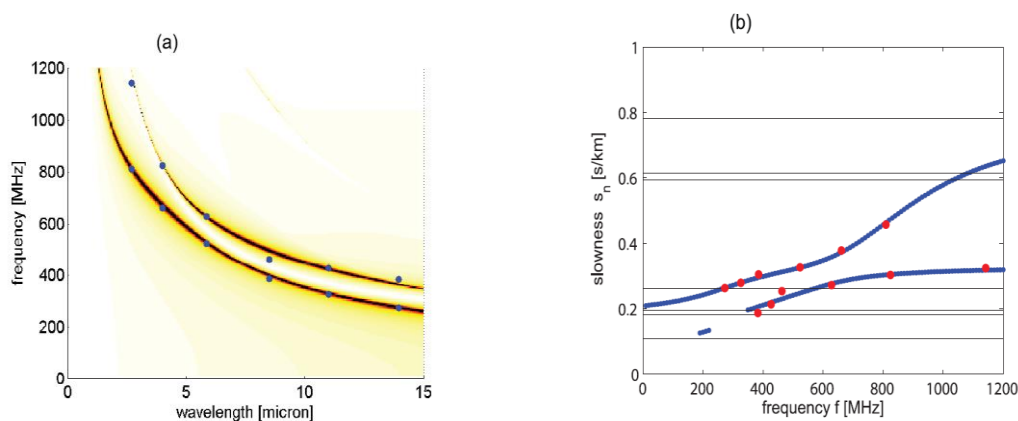


Fig.3: Experimental points (bold dots), Green matrix element level-line images (a) and slowness dispersion curves (b).

Both panels in Figure 3 illustrate the very good agreement between the experimental data, recorded in between 100MHz and 1.2GHz, and the theoretical model. We show in the right panel the slowness of the first two Rayleigh modes in the composite layer as a function of the frequency. From the best fit to the data, both the effective anisotropic Young's modulus $E_{x,z}$, Poisson's ratio $\nu_{x,z}$, and elastic constants of the composite layer C_{ij} , can be extracted.

4. Conclusion

Beside the dispersion properties of the nanostructures, it is worth noting that this experimental technique allows for a precise determination of the effective elastic parameters of such a layer on a substrate. It should also be noted that this non-destructive contactless technique is efficient to investigate the effective elastic properties at very high frequency (several GHz), along any directions of an anisotropic sample as are the phononic crystals and the elastic metamaterials. Moreover, while not described here, thermal properties of thin layers may also be investigated with this technique.

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