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Rapid and accurate analysis of surface and pseudo-surface waves using adaptive laser ultrasound techniques

Yi. Hong, Stephen D. Sharples, Matthew Clark, Michael G. Somekh *

School of Electrical and Electronic Engineering, University of Nottingham, Nottingham NG7 2RD, UK

Abstract

A method has been developed to measure the phase velocity of laser generated and detected surface acoustic waves. An optical grating produced by an electronically addressable spatial light modulator (SLM) was imaged onto the sample surface to generate surface acoustic waves whose frequency and wavefront was controlled by the SLM. When the grating period matched the surface acoustic wavelength, the surface wave was strongly excited, thus the wavelength and, thereby the phase velocity was determined. We present results with this method that allows the phase velocity and the angular dispersion of the generalized surface wave as well as the pseudo-surface wave on the (1 0 0) nickel to be measured. Measurements on (1 1 1) silicon single crystals are also presented. The measurement precision is approximately 0.2%. Methods to further improve the measurement precision are also discussed.

Keywords: Surface acoustic waves; Pseudo-surface waves; Anisotropy; Laser ultrasonics; Spatial light modulator

Surface acoustic waves (SAW) have been extensively studied to characterize the elastic properties of materials. Many techniques have been developed to determine the phase velocity of SAWs such as, acoustic microscopy [1], and more recently Brillouin scattering [2–4]. Contact techniques either suffer from the couplant perturbation or are restricted by the transducer dimension. Although, Brillouin scattering is non-contact, a high quality sample surface is required and the signal to noise ratio (SNR) tends to be rather poor due to the small proportion of Brillouin scattered photons resulting in extremely long measurement times. It has also been reported that there is a 3–4% systematic error in this measurement [2–4]. In the last two decades, the laser generation and detection of ultrasound has been developed and has proved to be a powerful tool to investigate SAWs. As a non-contact technique, it can work in hazardous environments and provide reliable measurements. By exploring the transient SAW pulse generated by short laser pulse the phase velocity can be determined accurately [5,6]. But, to obtain high temporal resolution, high-energy laser pulses are required, which can cause damage to the sample. Furthermore, the detection sensitivity is relatively low because the generated SAWs are broadband signals. To improve detection sensitivity without causing damage, some narrowband schemes have been proposed that used line arrays instead of a single line as the generating source [7,8], the reduced bandwidth improves the SNR. The problem that arises from these narrowband schemes is that they do not generally produce arrays with uniform spacing or well controlled intensity. The expected improvement in SNR is thus not achieved [8]. Even more important it is difficult and inconvenient to control the period of the linear arrays in the previously reported methods.

To overcome these difficulties, we have constructed an all-optical adaptive scanning acoustic microscope (O-SAM) with a spatial light modulator (SLM) to control the source distribution [9]. The use of the SLM allows us to generate arbitrary optical distributions from the source laser. The benefits are two fold: (1) by spreading the energy of the source laser, large SAW amplitudes can be generated below the damage threshold; (2) by tailoring the optical distribution of the source laser, the frequency and wavefront of the SAWs can be controlled in real-time, which enables it to adapt to variations in material properties. Here, we report a method using the O-SAM to measure the phase velocity of surface waves. Experimental results on single crystals are presented and the factors affecting the measurement precision and accuracy are discussed.

* Corresponding author. Fax: +44-115-951-5616.
E-mail address: mike.somekh@nottingham.ac.uk (M.G. Somekh).

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A schematic diagram of the O-SAM is shown in Fig. 1. Its detailed construction has been described elsewhere [10–12]. Briefly a Q-switched mode-locked Nd-YAG laser (82 MHz fundamental frequency) was used as the generating source. This optical energy from the pulsed laser was imaged to a size of 2.4 mm on the sample surface using the SLM; the image contained 512 * 512 programmable pixels. By programming the image on the SLM, the optical distribution of the source could be tailored, thereby controlling the properties of generated ultrasound. The ultrasound was detected with a modified knife-edge detector. To perform velocity measurement, the source pattern was set as a grating with the lines spaced uniformly to generate SAWs with a planar wavefront. The detector was positioned approximately 2 mm from the centre of the source. The output of the detector was observed and recorded with an oscilloscope. In the experiment, the grating period was changed progressively by programming the image parameters on the SLM. When the period matched the SAW wavelength, either at the fundamental frequency or a harmonic thereof, the SAWs are excited with maximum intensity. The resulting signal was then Fourier transformed to get the signal strength at the generation frequency so that a plot of signal strength as a function of grating period was obtained, as shown in Fig. 2.

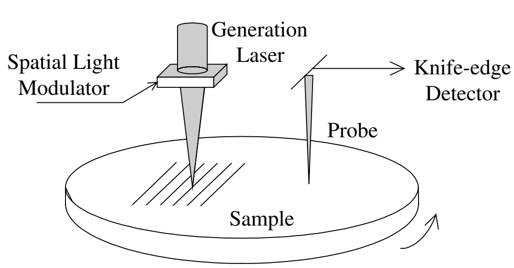

Fig. 1. Schematic diagram of experiment.

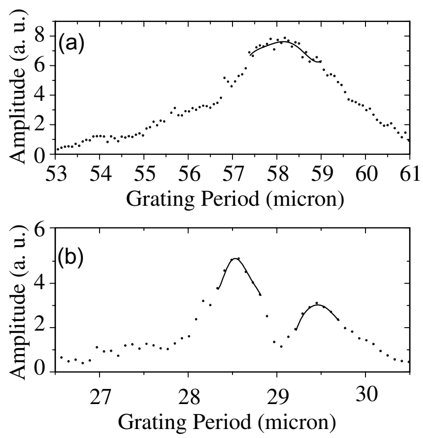

Fig. 2. Signal amplitude (circle) with grating period when propagating along 22° on the (1 1 1) oriented silicon, (a) at 82 MHz, (b) at 164 MHz, along with the fitting curve (solid).

Experimental values around the peak were smoothed using a polynomial fit. The peak of the smoothed curve corresponds to the wavelength of generated ultrasound, so that the phase velocity could be determined. The whole experiment was controlled by software and there was no mechanical movement involved, thus any uncertainty introduced by distance or time measurement was avoided.

Experiments were performed on a block of (1 0 0) oriented single crystal nickel, and an (1 1 1) oriented single crystal silicon wafer. The silicon wafer was 300 μm thick and coated with a 30 nm chrome thin film to increase the generating efficiency of acoustic waves. The angular dispersions of the samples were obtained by rotating the sample to measure the phase velocities along different propagation directions. The theoretical velocity was calculated with the partial wave method developed by Farnell [12] and used the elastic constants in Ref. [13].

On the (0 0 1) plane of Ni, measured phase velocities agreed well with theoretical values to within 10 ms^{-1} (Fig. 3) both for the generalized surface acoustic wave (GSAW) and for the pseudo-surface acoustic wave (PSAW). The phase velocities of the slow transverse wave (STW) are also displayed. We noted that, in the directions between 32° and 60°, the experimental velocity shows a sharp increase as the PSAW branch predominates and the GSAW signal disappears. In these directions, calculation reveals that the penetration depth of GSAW increases gradually and it behaves more like a bulk wave. As 45° approaches, it degenerates into a STW that is polarized transversely to its propagation direction. This tendency is accompanied with a decrease of normal displacement. Since the knife-edge detection relies on the gradient of surface displacement, the GSAW signal will vanish when it decreases below the detector sensitivity. Meanwhile, the PSAW, a high-speed SAW mode which radiates energy into the bulk and attenuates whilst propagating, emerges at 32° and diminishes at 58°. The attenuation of the PSAW on the (1 0 0) oriented Ni, however, is so small that the wave is

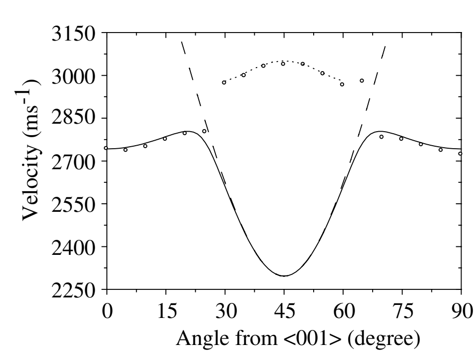

Fig. 3. Angular dispersions of the measured phase velocities (circle) at 82 MHz and the theoretical velocities of GSAW (solid), PSAW (dotted) and STW (dashed) on the (1 0 0) oriented nickel.

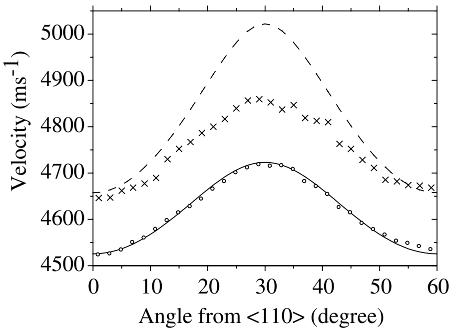

Fig. 4. Angular dispersions of the measured phase velocities of SAW (circle), the faster wave (cross) at 164 MHz and the theoretical velocities of GSAW (solid), STW (dashed) on the (1 1 1) oriented silicon.

easily detected in the experiment. The angular dispersion of experimental velocities shows mirror symmetry about 45° as expected.

Fig. 4 shows the phase velocities measured between ⟨1 1 0⟩ and ⟨1 0 1⟩ directions on the (1 1 1) oriented silicon, along with the theoretical velocities of GSAW and STW. As expected, the angular dispersion of experimental velocities had mirror symmetry about the direction of 30° and hexagonal symmetry in general. Notably, besides the GSAW, another wave mode was observed in all directions, which reproduced the symmetry of the GSAW but propagated with a higher velocity. The velocities of this wave approached those of the STW in some directions and were lower than the theoretical velocities of the PSAW (5300–5700 ms^{-1}). Considering the case of the Lamb wave in isotropic substrate, as the substrate thickness increases, the velocities of the a_0 and s_0 Lamb modes converge to the GSAW velocity and the velocities of the higher Lamb modes approached that of the STW [14]. The thickness of the silicon wafer used here was about 300 μm, far greater than the Lamb wavelengths. In this case, the faster wave observed is likely to be some higher order Lamb mode. Further experimental work including dispersion and attenuation measurements is still needed to identify this mode. It is also noteworthy that this wave was only observable when excited at harmonic frequencies of 164 MHz or more. The signal amplitude as a function of grating period at the direction of 22° is shown in Fig. 2. The first peak in Fig. 2(b) corresponds to the GSAW and the second corresponds to the faster wave. When excited at 82 MHz (Fig. 2(a)) the two peaks were not well resolved. In general at 82 MHz the resolution between modes is poorer since there were fewer grating periods with a corresponding reduction in the relative wavelength. Thus higher frequency excitation allows multiple wave modes to be better distinguished.

In this paper we have achieved measurement precision of approximately 0.2%, the method is at an early stage of development, but it is worth discussing some of the factors that may limit both the precision and the accuracy of the method. (1) The velocity is measured under the laser radiation. The slight DC heating caused by laser could depress the velocity slightly. (2) The limit of spatial resolution of the grating period is approximately 0.8 μm, which means that the precise SAW wavelength cannot be projected onto the sample, however, the excitation strength is a smooth function of grating period around the peak. Fitting a polynomial around this peak and taking the maximum of the polynomial ensures that the precision of determining the peak position is limited by signal to noise rather than quantization errors. (3) The uncertainty in the precise value of grating period due to the optical defocus errors might account for the main systematic errors in this method. These defocus errors can be eliminated by calibrating the size of the SLM image.

The method as presented offers a simple, rapid and convenient method of the phase velocity determination without recourse to the mechanical movement. We are currently investigating the feasibility of adapting this technique to measure the velocity of the wave outside the region where the laser excitation takes place, ideally this should be achieved without recourse to mechanical movement. The method we are investigating involves using a custom built linear detector. This can be arranged so that the detector elements are conjugate with different points along the direction of ultrasonic propagation. This means that provided, the magnification between the sample and the detector elements is known, the recorded phase along these elements (using electronics similar to that employed in [9]) will give an exceptionally accurate measure of the phase gradient and thus the velocity.

References

[1] W. Parmon, H.L. Bertoni, Ray interpretation of the material signature in the acoustic microscope, Electron. Lett. 15 (1979) 684.

[2] M. Mendik, S. Sathish, A. Kulik, G. Gremaud, P. Wachter, Surface acoustic wave studies on single-crystal nickel using Brillouin-scattering and scanning acoustic microscope, J. Appl. Phys. 71 (6) (1992) 2830.

[3] P.R. Stoddart, J.D. Comins, A.G. Every, Brillouin-scattering measurements of surface acoustic wave velocities in silicon at high-temperatures, Phys. Rev. B 51 (1995) 17574.

[4] M.H. Kuok, S.C. Ng, Z.L. Rang, T. Liu, Brillouin scattering from pseudosurface acoustic waves in (1 1 1) silicon, Solid State Commun. 110 (4) (1999) 185.

[5] A. Neubrand, P. Hess, Laser generation and detection of surface acoustic-waves—elastic properties of surface-layers, J. Appl. Phys. 71 (1) (1992) 227.

[6] H. Coufal, K. Meyer, R.K. Grygier, P. Hess, A. Neubrand, Precision-measurement of the surface-acoustic-wave velocity on silicon single-crystals using optical-excitation and detection, J. Acoust. Soc. Am. 95 (2) (1994) 1158.

[7] J. Jarzynski, Y.H. Berthelot, The use of optical fibers to enhance the laser generation of ultrasonic-waves, J. Acoust. Soc. Am. 85 (1) (1989) 158.

[8] J. Huang, S. Krishnaswamy, J.D. Achenbach, Laser Generation of narrow-band surface waves, J. Acoust. Soc. Am. 92 (5) (1992) 2527.

[9] S.D. Sharples, M. Clark, M.G. Somekh, Dynamic higher-order correction of acoustic aberration due to material microstructure, Appl. Phys. Lett. 81 (12) (2002) 2288.

[10] M. Clark, S.D. Sharples, M.G. Somekh, Fast, all-optical Rayleigh wave microscope: Imaging on isotropic and anisotropic materials, IEEE Trans. Ultrason. Ferroelect. Freq. Control 47 (1) (2000) 65.

[11] M. Clark, S.D. Sharples, M.G. Somekh, Non-contact acoustic microscopy, Meas. Sci. Technol. 11 (12) (2000) 1792.

[12] G.W. Farnell, in: W.P. Mason, R.N. Thurston (Eds.), Properties of Elastic Surface Waves, Physical Acoustics, vol. VI, Academic, New York, 1970, pp. 109–166.

[13] B.A. Auld, Acoustic Fields and Waves in Solids, Wiley, New York, 1973.

[14] I.A. Viktorov, Rayleigh and Lamb Waves, New York, Plenum, 1967.