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Picosecond ultrasonic measurements using an optical mask

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In this paper we describe results obtained using a variation of the picosecond ultrasonics technique. We place a transparent optical mask very close to the surface of the sample. The lower surface of the mask has a series of grooves to produce a variation of the intensity of the pump and probe light pulses across the surface of the sample. Because the light intensity varies with position, the application of the pump light pulse can generate surface acoustic waves with a wavelength equal to the period of the mask. We report results obtained in this way and discuss the possible practical applications of this new approach.

1. Introduction

The picosecond ultrasonics technique [1] makes it possible to perform ultrasonic experiments on a wide variety of planar nanostructures, i.e., structures consisting of a sequence of thin films deposited onto a substrate. It also provides a way to measure the attenuation of sound at frequencies of 1 THz and above [2,3]. In the normal configuration a pump light pulse of duration 1 ps or less is directed onto an area of the sample surface. The absorbed light sets up a thermal stress which launches a strain pulse into the sample. This strain pulse propagates into the sample and is partially reflected at each interface that it encounters. When the resulting echoes return to the sample surface there is a small change $\Delta R(t)$ in the optical reflectivity of the sample and this change is measured using a time-delayed probe light pulse. In the normal configuration a pump light pulse is directed onto an area of the sample surface which has linear dimensions ξ of some tens of microns. Because ξ is usually much larger than the distance that the light penetrates into the sample, the generated sound is a longitudinal strain pulse with particle displacement normal to the sample surface. Through the use of specially prepared samples, it has also been possible to generate transverse sound [4–6].

To generate surface acoustic waves (Rayleigh waves) one approach has been to pattern the sample surface so that the temperature rise of the surface resulting from the application of the pump pulse varies periodically across the surface [7–9]. Patterning the sample surface has the disadvantage that the geometry of the sample is modified; thus as far as a practical application for metrology purposes it cannot be considered to be a non-destructive technique. A second approach has been to use a transient grating method [10], a well-established technique in ultrafast optics [11]. In this method the pump light is divided into two beams directed at the sample at angles of plus and minus θ relative to the normal to the surface. This gives an intensity which varies with period $\lambda/2\sin\theta$, where λ is the pump wavelength. This method is thus limited by the shortest possible wavelength available, and also requires a slightly more complicated optical setup than is required for the standard pump-probe experiment [12,13].

In this paper we describe an alternative method for the generation and detection of surface acoustic waves. We place an optical mask close to the surface of the sample in order to produce a variation of the intensity of both the pump and probe light pulses across the surface of the sample. Using this technique we are able to generate and detect surface acoustic waves with a wavelength equal to the period of the mask. There is only a very light contact between the mask and the sample, and thus the method is non-destructive. The wavelength of the surface waves is equal to the period w of the mask, or the period divided by an integer. Thus, this can be chosen to have any desired value subject to some limitations discussed below.

We describe the experimental setup in Section 2 and give the results of computer simulations that we have performed to investigate how close the mask needs to be to the surface. Section 3

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presents the experimental results and compares these with theoretical calculations of the surface wave velocity.

At the same time as this work was submitted, a very similar approach was described in a paper by Li et al. [14].

2. Experiment

The measurements reported here used a standard pump-probe optical setup based on a Spectra Physics Mai Tai laser with wavelength 800 nm, producing 200 fs pulses with a repetition rate of 80 MHz.

For the mask we used the structure fabricated by the method shown schematically in Fig. 1. A chromium film of thickness 5 nm was deposited onto a silica wafer, and then coated with photoresist (PR) (a), the photoresist was patterned using holographic lithography (b), and then the Cr film was patterned by etching through the gaps in the photoresist (c), the photoresist was removed (d), trenches were next formed in the silica substrate by etching through the gaps in the Cr (e), the chromium was then removed (f), and finally, a 50 nm layer of TiO_2 (this was added because of its high refractive index) was applied to the structure by atomic layer deposition (g). The repeat distance w of the mask was measured by scanning electron microscopy (SEM) to be 550 nm (see Fig. 2).

In an earlier attempt at an experiment of the type presented here, we simply rested a mask directly onto the surface of the sample [15]. The mask had a repeat distance of 1 μm and was on a ~1 μm aluminum film on a silicon substrate. We were able to detect a surface wave of frequency 2.73 GHz; this frequency was in reasonable agreement with that expected from the mask period and a calculation of the velocity of Rayleigh waves in Al. However, the signal to noise ratio in the experiment was poor, and often the mask would be placed on the sample but no signal due to surface waves was detected. It was natural to assume that the failure to observe a signal was the result of dirt on the sample, the lower side of the mask, or both. To minimize the chance of a dirt particle preventing the close proximity of the mask to the sample, in the present experiments we have carefully cleaned both surfaces and have performed the experiment inside a mini clean room positioned on the optical table. We have also reduced the area of the mask to 2 mm by 6 mm to decrease the chance for it resting on a dirt particle somewhere on the sample.

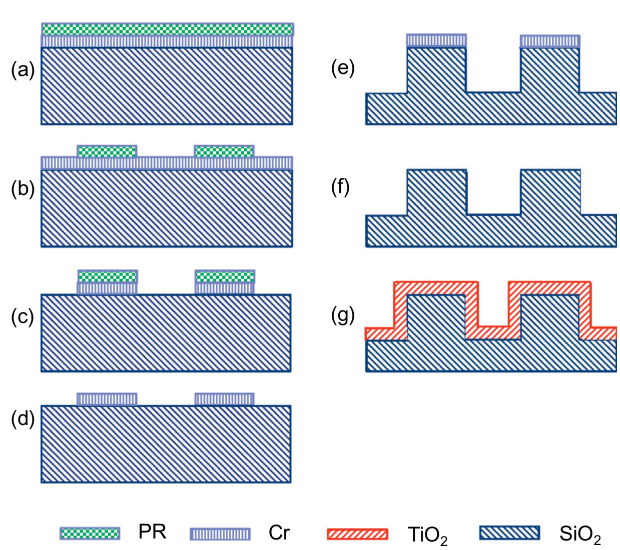

Fig. 1. Steps in fabrication of the optical mask.

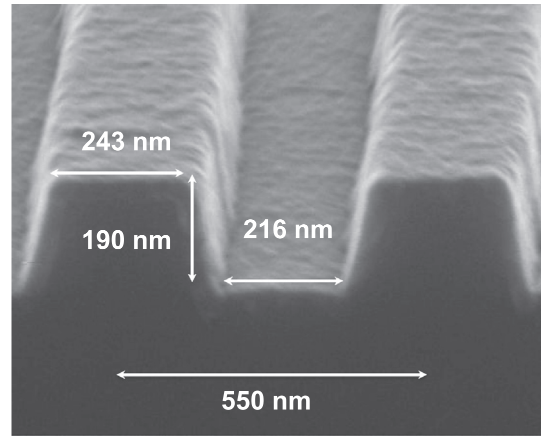

Fig. 2. Scanning electron microscope image of the optical mask.

The samples were aluminum films sputtered onto silicon wafers. The thickness of the Al was measured using SEM. The mask was positioned above the sample surface using a precision stage. The spacing between the invar plate holding the mask and the sample holder was monitored by three capacitive sensors, and the output from these sensors was used to control piezo-actuators which adjusted the separation and orientation. This stage made it possible to maintain the separation distance between the mask and the sample to an accuracy of approximately ±1 nm (but see discussion in next section), and the angular orientation of the mask could be controlled to $\pm 10^{-4}$ radians. To check that the mask was parallel to the sample surface, the direction of a He–Ne laser beam reflected from the mask was compared to the direction of light reflected from the sample. The pump and probe beams were focused onto spots of diameter 20 μm. With the angular control just mentioned, this meant that the variation in the spacing between the mask and the sample across the area of the beam spot was of the order of 2 nm.

One expects that as the distance of the mask from the sample surface increases, the light intensity at the sample will become more uniform and the amplitude of the generated surface waves will decrease. It is therefore of interest to know how close the mask has to be to the surface in order for efficient generation and detection of surface waves, and we have performed simulations to investigate this. We wrote a FORTRAN program based on the rigorous coupled-wave analysis (RCWA) method [16] to simulate the electromagnetic field in the grating and on the sample surface resulting from an incident light wave. It is important to note that the requirements for optimizing the generation and detection are complicated and not the same. Let the normal to the sample surface be the z-direction ([001] direction of the Si) and the x-direction be along the surface ([100] direction of the Si), and let the period of the grating be w. These orientations were chosen to match the experimental setup. If the energy deposited by the pump pulse into the sample per unit distance along the x-axis is $f(x)$ then the amplitude of the generated surface wave with wavelength λ will be proportional to the Fourier component $f(q)$ of this, with $q = 2\pi/\lambda$. However, this relies on some approximations. It assumes that the light penetrates into the sample the same distance for each value of x. In addition, heat conduction may significantly modify the energy distribution. The detection of surface waves is also complicated. The propagating surface wave will result in both a displacement of the surface and a change Δr in the optical reflectivity (dependent on x) coming from the piezo-optic effect. Both the displacement and Δr will contribute to the overall change in reflectivity of the probe light.