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Direct measurement of surface displacement of metal thin films in picosecond laser ultrasonics

ピコ秒超音波法における金属薄膜表面変位の直接測定

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1. Introduction

Picosecond acoustic pulses can be generated in materials by ultrashort light pulses [1]. In case of metals, the acoustic pulse generation by the light absorption is based on the thermo-elastic process. But if one looks at the process in detail, it turns out to be much more complicated. First the light pulses are absorbed by the electrons near the sample surface. These nonequilibrium electrons are thermalized locally in the electron system to form an inhomogeneous electron temperature distribution (hot electrons). Concurrently, the hot electrons diffuse and transfer their excess energy to the lattice of the medium. In this way, a spatiotemporal variation of the lattice temperature field is formed. The thermal stress caused by the lattice temperature rise generates the acoustic pulses. In this way the pulse generation mechanism is governed by various processes, and the measurement of the shape of the strain pulses is useful for the investigation of these processes [2-4].

The strain pulse shape can be derived from the surface displacement of the sample. To measure this, the optical pump and probe technique can be exploited [5]. The propagation of acoustic pulses generated by the pump light pulses is monitored as optical transient phase changes using delayed probe light pulses. However, the detected phase changes are also affected by the photoelastic effect [6]. It is difficult to distinguish between these two contributions.

2. Theory

For an optically isotropic, opaque semi-infinite sample, the reflectance changes for *s* and *p* polarized probe light are expressed as

$$\frac{\delta r_s}{r_s} = iA + \alpha B, \qquad \frac{\delta r_p}{r_p} = iA + \beta B \qquad (1)$$

respectively, where A is a real quantity and is proportional to the surface displacement, and B is a complex quantity related to the photoelastic effect [6]. The quantities α and β are complex constants. The difference between the complex reflectance changes for the *s* and *p* polarized probe light arises only through the constants α and β. So A can be deduced from these experimentally obtainable reflectance changes.

However the accuracy of this method is not sufficient in practice owing to the need to take two independent measurements for the *s* and *p* polarizations. To avoid this difficulty, we propose an interferometer for the direct measurement of the surface displacement using the mixture of the *s* and *p* polarization components for the probe light. The total electric field amplitude is proportional to $r_s(1+iA+\alpha B)+\mu r_p(1+iA+\beta B)$, where the complex constant μ includes an amplitude scaling factor and a phase shift between the *s* and *p* polarization components. To cancel out the photoelastic effect, we choose μ to extinguish the term including B. Then the resulted amplitude is proportional to $(1+iA)$. Since A is the real quantity, we need to use another interferometer to detect A as the intensity variation.

3. Experimental setup

The measurement is done on a thin film of Cr of thickness 310 nm deposited on a crown glass substrate. Light pulses from a mode-locked Ti-sapphire laser with pulse width 100 fs, repetition rate 82 MHz, and wavelength 830 nm are used to generate acoustic pulses in the film (pump light). The light pulses from the same laser are frequency doubled to have wavelength 415 nm by a β-$BaBO_4$ crystal (probe light), and are delayed to detect the transient variation of the reflectance. To exploit the *s* and *p* polarizations, the probe light is obliquely incident on the sample with an incident angle of 45°. Initial tests on this technique have proved the concept works [7].

4. Results

The relative reflectance change of the probe light $\delta r/r$ is a complex quantity, and is expressed as

$$\frac{\delta r}{r} \equiv \rho + i\delta\varphi\,, \qquad (2)$$

where ρ and $\delta\varphi$ are the real and imaginary parts of the reflectance change, respectively. The former is caused only by the photoelastic effect, whereas the latter caused by the surface displacement and the

photoelastic effect.

The results of the experiments on a thin film of Cr are shown in **Fig. 1**. The curves (a)-(d) are the real (ρ) and imaginary ($\delta\varphi$) parts of the relative reflectance changes obtained using conventional interferometric measurements with *s* or *p* polarized probe light [5]. The curve (e) is the real part of the reflectance at the condition for the cancellation of the photoelastic effect. By mixing reference light with a $\pm\pi/2$ phase difference, the surface displacement change is obtained, as shown in the curves (f) and (g). The surface displacement obtained is quite different from the curves (b) or (d), which are heavily distorted by the photoelastic effect.

5. Conclusion

We have demonstrated the direct measurement of the surface displacement in laser picosecond ultrasonics for a thin metal film. This should prove to be a useful method for the analysis of the strain pulse shape in metals and semiconductors.

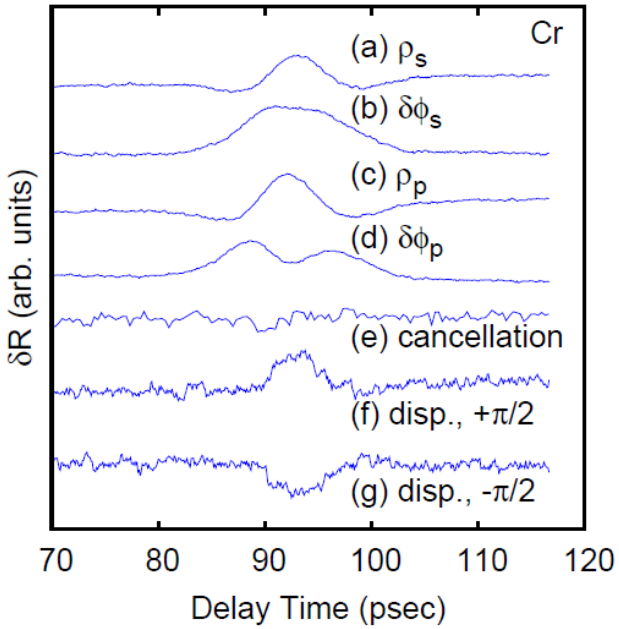

Fig. 1 (a)-(d): the real (ρ) and imaginary ($\delta\varphi$) parts of the relative reflectance changes corresponding to the first echo with *s* and *p* polarized probe light by conventional measurement. (e): the cancellation of the peak caused by the photoelastic effect by adjusting the amplitude ratio and relative phase difference of the *s* and *p* polarized probe light. (f) and (g): the direct measurement of the surface displacement. The signal polarity is flipped according to the π-phase difference of the reference light.

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