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Nanoscale mechanical contacts probed with picosecond acoustic phonons and ultrafast electron diffusion

ピコ秒音響波と超高速電子拡散を用いた
コンタクトメカニクスの観察

Yohei Iwasaki[1‡], Thomas Dehoux [1], Oliver B. Wright[1]
([1] Grad. Sch. Eng., Hokkaido Univ., Sapporo, Japan)
岩崎洋平 [1‡], Thomas Dehoux[1], Oliver B. Wright[1]
([1] 北海道大 工)

1. Introduction

The contact between two objects is a common phenomenon in daily life. On a microscopic scale there are in fact a lot of contact points because of the inherent roughness of surfaces. In contact mechanics, Hertz proposed a generic theory[1]. This applies to frictionless elastic contact between two spheres or between a sphere and a flat surface. In order to investigate contacts on a microscopic scale, one normally should unload the contact first in order to examine the contact region. An example is the use of sharp probes, such as pyramidal indenters or the tips in atomic force microscopes[2]. To better investigate the mechanisms of contact during loading one can use ultrasonics[3]. However, so far the wavelength of the sound was limited to the millimeter region (or MHz frequencies). Here we greatly extend the frequency range using picosecond ultrasonics[4] to generate nanometer scale acoustic wavelengths (~100 GHz frequencies) for the investigation of nanometer scale indentations in the contact region.

In addition, the use of an ultrafast optical pump-probe method allows us to use ultrafast electron diffusion[5-6] to investigate mechanical contacts for the first time.

2. Experimental setup

We prepared two samples consisting of a sapphire ball of radius 1 mm and a sapphire plate of thickness 1 mm on which are evaporated 50 nm gold films. The samples lie horizontally on a rigid and pierced holder to allow optical access from underneath. A schematic diagram of the setup is shown in **Fig. 1**. The principal crystal axes of the ball and plate are arranged to be vertical.

The ball is pressed against the plate using a displacement stage. We can monitor the load with a load cell. The optics is shown in **Fig. 2**. We use the optical pump and probe technique with 200 fs duration pulses from a mode-locked Ti:Sapphire

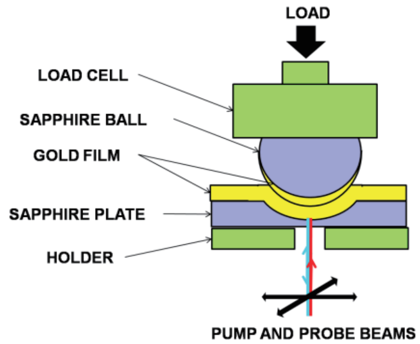

Fig. 1 Setup

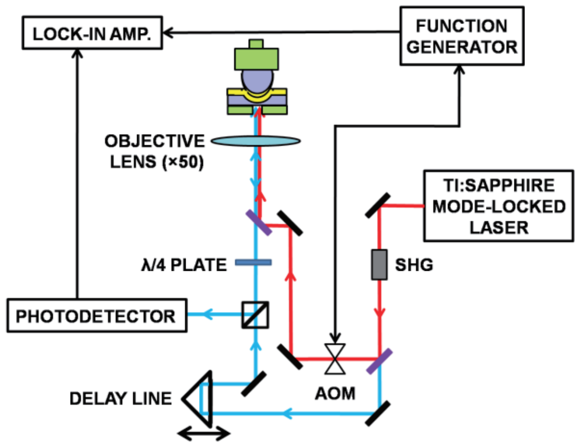

Fig. 2 Optics. AOM: acousto-optic modulator, SHG: second harmonic generation crystal

laser (with a repetition rate of 80 MHz and a central wavelength 810 nm). The pump beam is chopped at a frequency of 1.1 MHz for synchronous lock-in detection. The frequency-doubled probe beam goes through a delay line. The pump and probe beams are both focused on the plate-gold interface with a ×50 objective lens with spot diameters 2 μm and 1 μm, respectively. Picosecond longitudinal acoustic pulses and nonequilibrium electrons are generated in the gold films at the plate-gold interface. The optical reflectivity change at this interface is measured with the probe beam as a function of the time delay t between the pump and probe pulses. The objective lens is scanned to probe different

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e-mail address: yyy@eng.hokudai.ac.jp

regions of the contact area.

3. Experimental results

We measure the reflectivity change as a function of delay time *t*. From this we investigate both acoustic strain pulse propagation and nonequilibrium electron diffusion.

The acoustic strain pulses generated in the gold film are reflected from the gold-film surface, and are then detected at the plate-gold interface. The normalized echo amplitude is plotted against radial position (of the surface of the contact area) for a load of 1 N in **Fig. 3**. In the contact area, this amplitude decreases because of the change in acoustic reflectivity coefficient at the contacting interfaces. The radius of the contact area deduced from Fig. 3 is 25 μm, in rough agreement with Hertz theory (ignoring the gold films).

We also observe a sharp change in the reflectivity at *t*=0, mainly proportional to the temperature change of nonequilibrium electrons in the probed region[7]. We have succeed in measuring a difference in this sharp change in and out of contact.

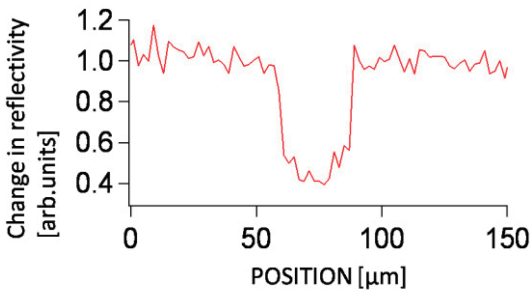

Fig.3 Normalized change of reflectivity vs. the radial position of the surface of contact area at 1 N load.

4. Conclusions

In conclusion, we have applied an ultrafast optical technique to probe the mechanical contact between a sapphire plate by a sapphire sphere. Contrast based on acoustic pulse reflection and based on nonequilibrium electron diffusion was simultaneously obtained. These measurement methods should be useful for the in-situ investigation of mechanical contacts between different solids.

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