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Ruby films as surface temperature and pressure sensors

Ursula J. Gibson
Dartmouth College

Maxim Chernuschenko
Dartmouth College

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Ursula J.Gibson and Maxim Chernuschenko

Thayer School of Engineering , Dartmouth College, Hanover NH 03755-8000 USA

u.gibson@dartmouth.edu

Abstract: Epitaxial films of chromium doped alumina, 0.3 microns in thickness, were grown on single crystal sapphire substrates for use as surface thermometers. Curve fitting was performed on the R1 and R2 fluorescence peaks, and the line widths and peak shifts were used to determine the temperature of the surface during sliding contact with a variety of plastic bearings. Temperatures could be determined with a repeatability of 2 degrees C, and adequate signal for temperature determination could be obtained in 30-100 msec. in dots that were 200 microns in diameter, using a 0.25 watt argon laser. Both average (nominal) and local temperature increases were measured. Pressure-induced shifts could be treated as an error to the temperature determination.

OCIS codes: (160.1890) Detector materials; (120.6780) Temperature

References and links

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1. Introduction

Optical measurement of temperature and pressure has several advantages – the sensors are environmentally rugged, remotely probed, immune to electromagnetic interference, can be made small, and require no electrical input leads. Optical sensors can utilize interference, birefringence, absorption, blackbody radiation, or fluorescence. Fluorescence-based thermometers can be based on any of several changes in the optical response of the active material [1]. Changes in the relative intensity of multiple peaks, changes in overall intensity, line shifts and fluorescence lifetimes can all be the basis for a sensor. $Cr3^+$ containing crystals have been used extensively to measure temperature and pressure. In particular, $Cr:Al_2O_3$, or ruby, has been exploited because of its high efficiency. The ruby R1 and R2 lines, excited by a broadband or laser source, have well-characterized fluorescence behavior as a function of temperature and pressure. The pressure shift is the standard NIST-based pressure calibration

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method for the preponderance of diamond-anvil pressure experiments [2]. The temperature shift is somewhat larger, and was characterized extensively by Kiel [3], McCumber and Sturge[4] in the 1960's and by Ragan et al [5] thereafter. There is very little line broadening associated with increases in hydrostatic pressure, while increases in temperature lead to significant line width changes, and changes in the relative intensities of the two peaks. Figure 1 shows the pressure and temperature dependence of the ruby R-lines. In principle, it is possible to deconvolve the pressure and temperature, as pointed out by Yamaoka et. al. [6]

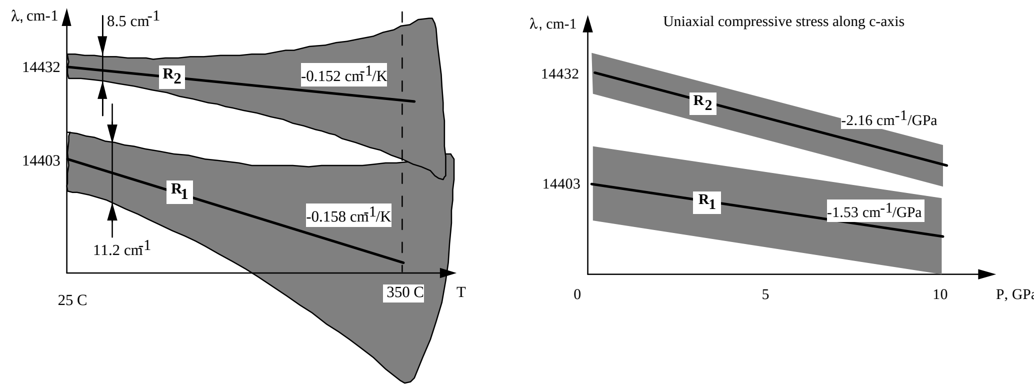

Fig. 1 Ruby R-line dependences

contributions to the line shape under hydrostatic conditions. Recently, Wen et. al. [7] developed a technique for growing epitaxial doped layers on single crystal pure alumina substrates, for use as pressure sensors. We have used similar samples for the detection of the temperature rise under low pressure conditions. Application of such sensors include measurement of surface temperature during sliding/rolling contact, such as is encountered in mechanical bearings and hard disk sliders. We have chosen to work in the low-pressure, high surface-speed regime, so that the pressure contribution to the line shift can be treated as an uncertainty in a temperature determination. The use of thin (0.3 micrometer) and photolithographically defined sensors of diameters down to 100 microns allow us to determine the local temperature at the point of contact. Gating of the excitation pulse permits temporal resolution of the contact events.

2. Experimental

Our measurements are based on a microraman setup, comprised of an argon laser, a microscope to deliver the excitation and collect the fluorescent signal, a monochromator, and a CCD camera for parallel acquisition of the fluorescence spectrum. The samples are prepared in a manner similar to that described by Wen, et. al.[7]. A single crystal substrate from Crystal Systems, Inc, with very low Cr impurity levels, is covered with a five layer composite film of alumina and Cr, with respective layer thicknesses of 1000 and 30 Å. The substrate is photolithographically masked before the film deposition to define a series of

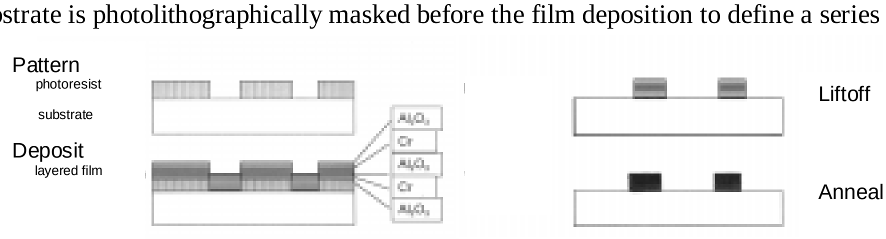

Fig. 2 Sample preparation process

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circular active regions with diameters from 100 to 500 microns, as illustrated in Figure 2. After liftoff of the remaining film, the substrate is annealed at 1300 °C for a period of three to seven hours. The resulting film has strong R-line emission, with an R2 linewidth that is inhomogeneously broadened to approximately 11 cm^{-1}. The measurement optics are shown in Figure 3. A 0.25 watt argon laser illuminates the sample through a

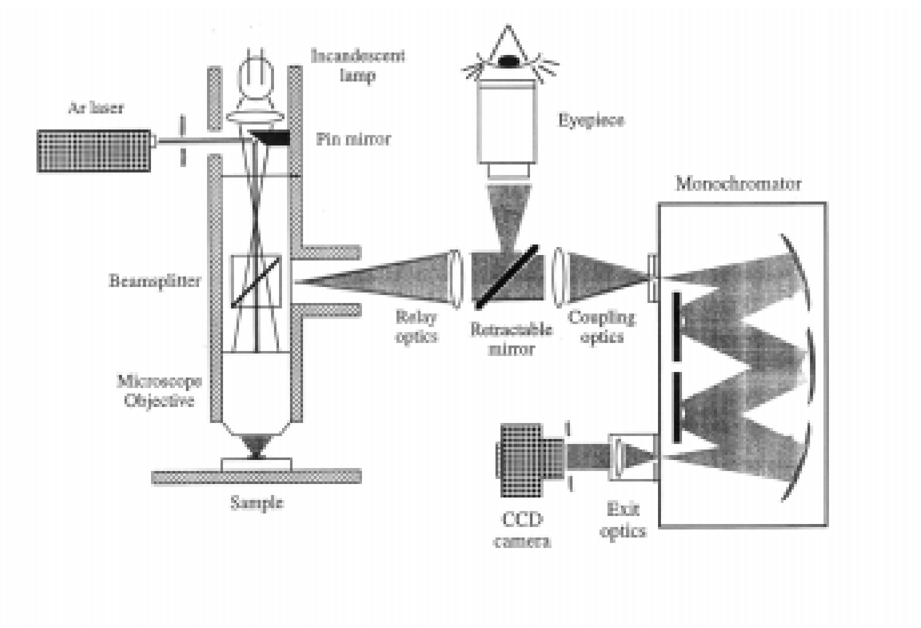

Fig. 3 Optical layout of the measurement system

microscope, and the fluorescence signal is collected by the microscope objective, separated from the excitation light with a beam splitter, and focused on the entrance slits of a double pass Jobin-Yvon 1 m monochromator. The exit slits are wide open, and the fluorescence signal is focused onto the detector plane of a Santa Barbara Instrument Group CCD camera. The image of the spectrum is then collected in vertical bins on the 2-d array to yield an intensity vs. wavenumber spectrum. Neon lines were used for calibration of the signal, and the line position changes are measured relative to their room temperature values. The microscope has a removable mirror that can be used with a white light source to align the

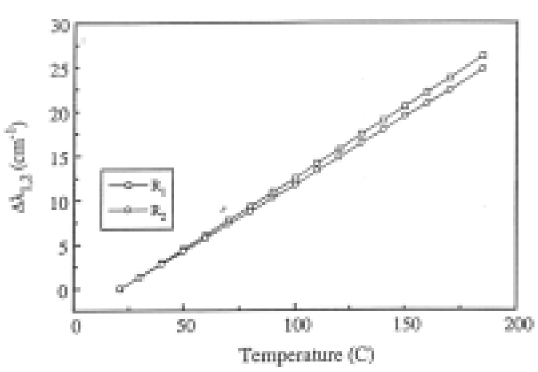

Fig. 4 R_1 and R_2 line shifts as a function of temperature

sample with the excitation beam, and observe the contact area during sliding experiments. Figure 4 shows a calibration curve, obtained by comparing readings from a thin film thermocouple and the ruby excitation during quasi-static heating experiments. Line widths and intensity ratios were also measured as a function of temperature, but had lower signal to noise ratios than did the line shift. Measurement of the line shift during static pressure calibrations yielded shifts of less than 0.5 cm^{-1} for the pressure range that we used during sliding tests. We therefore treat the pressure contribution as an error signal to the temperature measurements in the subsequent discussion. Line widths were unaffected by pressure, as expected.

Sliding experiments were made in a ball on disk configuration, using the mechanical setup shown in Figure 5. A lever arm applies the load in the location indicated by F. The

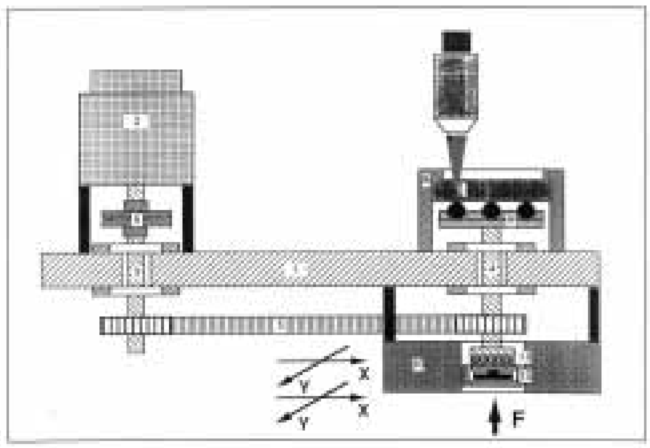

Fig. 5 Mechanical design of tribological tester

load is measured using a load cell, and a thrust bearing permits rotation of the platen containing three balls that contact the sensor region. A motor with attached tachometer drives the rotation using a belt and without affecting the load. The balls that were used in our dry sliding experiments were made of teflon, delrin, lucite and nylon 66. Sliding speeds were 0.1 to 0.7 m/sec and loads were 4-11 N/ball. The ratio of thermal conductivities of the substrate and ball were such that almost all heat was delivered to the substrate (Pechlet number of 250). The two quantities of interest are the nominal temperature rise (the average temperature to which the substrate rises), and the local temperature excursions during the contact events. The nominal temperature rise was measured with dc excitation and a CCD exposure that averaged over many contact events. The local temperature rise that is reported was obtained by averaging over many 1 msec windows by triggering at the same point in the cycle each time. The argon laser was triggered by a pulse from a HeNe laser reflecting off a mirror on the drive shaft. The delay between the trigger and the excitation pulse was varied to scan the contact event, as shown schematically in Figure 6. For each measurement, the sliding balls

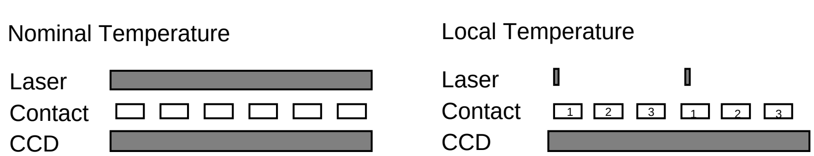

Fig. 6 Schematic showing the relationship between the laser excitation, the ball-bearing contact time and the CCD camera shutter opening. The contact time of the ball is exaggerated.

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were "run-in" to eliminate large changes in contact area during the measurement period. New balls were used for each run, using this procedure. For measurements of the local temperature, the apparatus was run until the nominal temperature had stabilized before acquiring data. The laser was used to illuminate the contact event of one of the three balls, to reduce errors due to tracking differences if the balls were imperfectly aligned.

3. Results and Discussion

Typical results for the nominal temperature rise for Teflon sliding against sapphire are shown in Figure 7, for loads of 4,7.6, and 11.2 N, and a sliding speed of 0.25 m/sec. The temperature

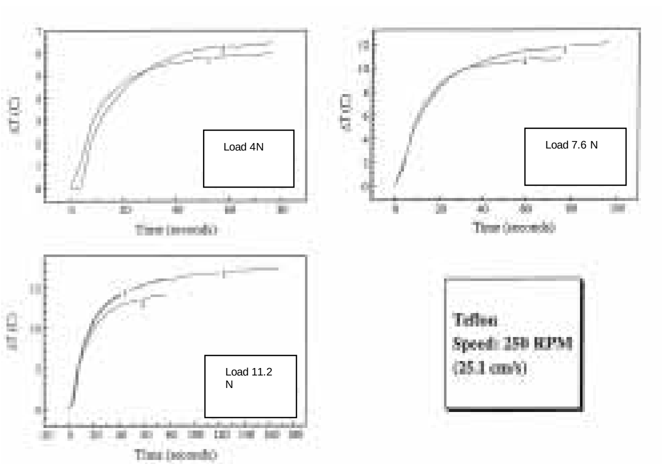

Fig. 7 Nominal temperature rise for teflon sliding against sapphire

rise increases with increasing load, with a maximum rise of approximately 15 degrees. Multiple curves on each plot indicate the repeatability of the result. Figure 8 is a similar plot

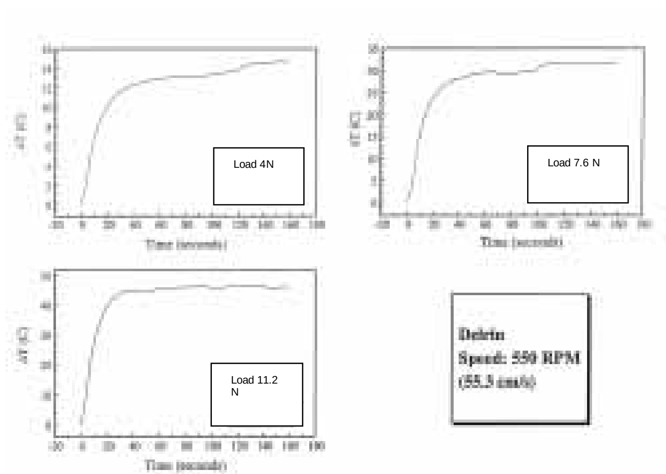

Fig. 8 Nominal temperature rise for Delrin against sapphire

for delrin sliding on sapphire at 0.55m/sec. The average temperature is higher, due to the higher friction coefficient, increasing with applied load, but equilibrating in a similar length of time. The signal collection times for these curves were typically 0.1 sec, with a 1.0 sec delay

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between CCD frames. Figure 9 shows the results of a local temperature measurement. This data was obtained using a 1 msec argon pulse, and averaging over 40 contact events. As the

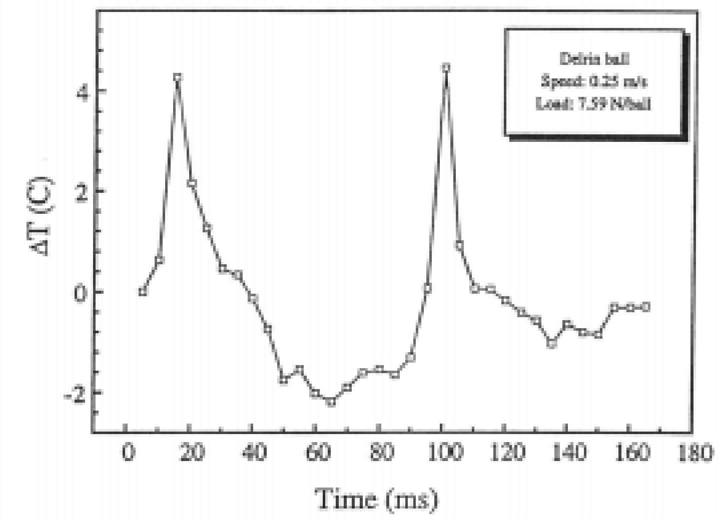

Figure 9 Local temperature rise during the contact event as a function of delay time of the excitation pulse

balls did not follow identical tracks on the sensor surface, only contacts with one ball were averaged together. The curve shown is the temperature rise above an equilibrated nominal temperature rise of 9 °C.

4. Summary

We have demonstrated the use of the spectral shifts of ruby fluorescence lines for the measurement of the temperature during sliding contact. The volume of the sensor is less than 4×10^{-8} cm^3, the lateral resolution is less than 400 μm^2, and the single shot temporal resolution is 50msec, using a 0.25 watt excitation laser. Better time resolution was possible using a gated excitation pulse and a synchronizing trigger with a variable delay. This technique has been applied to the measurement of surface temperatures during sliding contact under conditions of low load and high sliding speeds. We are presently investigating the possibility of determining pressure and temperature simultaneously with higher loads and lower speeds.

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