Thermal Conductance through Sapphire-Sapphire Bonding

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Abstract

Thermal conductance on sapphire-sapphire bonded interface has been investigated. Two pieces of single crystal sapphire bar with square cross section were bonded together by adhesion free bonding. In two sections of the bar, thermal conductivity was measured between 5 K to 300K. One section contains a bonded interface and the other section measured a thermal conductivity of the sapphire as a reference. No significant thermal resistance due to bonded interface was found from this measurement. Obtained thermal conductivity reaches $\kappa \simeq 1 \times 10^4$ [W/m·K] in temperature range of $T = 20 \sim 30$ K which is a planned operating temperature of a cryogenic mirror of the Large scale Cryogenic Gravitational wave Telescope. It looks promising for sapphire bonding technique to improve a heat transfer from a large cryogenic mirror to suspension wires.

1. Introduction

Cryogenic mirror is one of the key issue in an advanced interferometric GW detector such as LCGT[1]. Purpose of a cryogenic mirror is to reduce thermal noise of the mirror. After some pioneering studies, a basic configuration of a cryogenic mirror has been described [2, 3]. Two loops of sapphire fibre suspend a mirror made by sapphire single crystal. A heat generated by irradiation of intense laser light is transferred through sapphire fibers from the mirror to a cold bath. Depending on the properties of sapphire material, operating temperature of the cryogenic mirror is designed about $T \simeq 20$ K.

In a current design of the cryogenic mirror, heat flows from the mirror to suspension fibers through elastic contact between them. An actual area of contact may be very small because only a weight of the mirror produces contact force. This small area of contact may cause an additional thermal resistance on a heat path of cooling mirror [2].

pp. 3131–3134

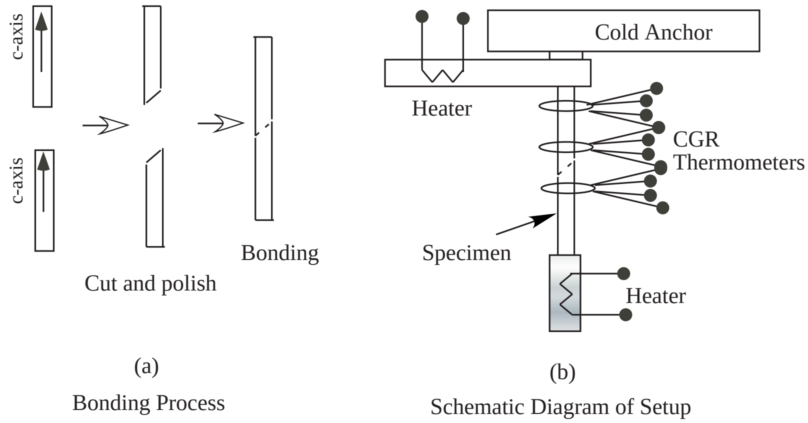

Fig. 1. (a) Bonding process of sapphire bar. One end of each bar were cut 45^o and polished to make surfaces to be bonded. Final size of a bar was 4.0 mm $\times$ 4.0 mm $\times$ 59mm. (b) Schematic diagram of a setup for thermal conductivity measurement. Three of CGR thermometers were put on the bar. A bonded interface was located between the middle thermometer and the lower thermometer. In the section between the upper thermometer and the middle thermometer, we measured thermal conductivity of sapphire substrate. Current input wires of three thermometers were connected in series for supplying a common excitation current. Two heaters were attached at bottom and top of the bar. The top heater controlled a offset of temperature and the bottom heater supplied a heat current for measurement.

In order to avoid the thermal resistance of elastic contact, bonding of sapphire may be useful. There are some techniques applicable to sapphire bonding such as metalizing method, chemical bonding just like a case of fused silica [4] and direct bonding [5]. For our purpose of sapphire bonding, a bonded interface should have thermal conductance as large as the thermal conductance of sapphire substrate. Also the interface should not introduce an additional mechanical loss compared with the basic configuration. So the method which do not use any intermediate material may be suitable.

As a first step to apply sapphire bonding to the cryogenic mirror, we measured thermal conductivity of a bonded sapphire bar at cryogenic temperature. The specimen was prepared from pieces of high quality sapphire crystal and the adhesion free bonding method that is commercially available by ONYX Optics, Inc.

2. Method of Experiment

Bonding process and an experimental setup are shown in Fig.1.

A HEMEX grade sapphire crystal was supplied by Crystal Systems, Inc.. Long side of bars coincides c-axis of the crystal. Two bars were bonded together to make a straight bar. The size of cross section was 4.0 mm $\times$ 4.0 mm measured by a slide caliper at both ends of the bar. A bonded interface was hard to find after bonding even by scattering of thin laser light. Two sections of the bar were used for thermal conductivity measurement as shown in Fig.1(b). Each CGR thermometer was set into a small hole of the aluminium clamp in order to fix on the bar. In-between the aluminium clamp and the surface of the bar, we put a ϕ0.1 mm pure Al wire to confirm a location of contact. Interval of the thin wires was 10.0 mm for between the lower and the middle and was 10.5 mm for between the upper and the middle. An estimated error of thin wire location was about 0.5 mm.

An assembly was put into a vacuum chamber ($\sim \phi$200 mm $\times$ 300 mm) and cooled by liquid helium. A pressure inside the chamber was kept $p \simeq 1 \times 10^{-4}$ Pa during the measurement. Heat leakage along wires of thermometers and heaters was avoided carefully.

Measurements were performed in steady state of temperature distribution. An offset temperature and a heat flux through the specimen were controlled by two heaters. Output voltages of CGR thermometers were monitored by DMM. Excitation current for thermometers were adjusted as keeping a readout of the DMM about 1 mV $\sim$ 3mV. If the readout excess 3mV, self-heating of thermometer may cause an error. If the readout is smaller than 1mV, an influence of fluctuation may increase.

Influence of parasitic thermo-electric force was cancelled by subtracting a readout with normal current and a readout with inverted current.

3. Results

Figure 2 shows the results as thermal conductivity of the sapphire bar in temperature of 6 K to 290 K. Error of each point are caused from fluctuation of DMM readout. A 5% error due to the location of thermometers is smaller than these sizes shown on Fig.2.

No significant differences of thermal conductivity are found between the section of sapphire substrate and the section with bonded interface. Also the obtained value of thermal conductivity well coincide with values recommended in a data book (Touloukian Y.S., DeWitt D.D. , Thermophysical Properties of Matter(1972, Plenum).).

4. Discussions

The bonded interface shows good thermal conductance from 6 K to 290 K. The technique of adhesion free bonding is promising to avoid an excess thermal resistance between a contact of mirror and suspension wire in LCGT. Further investigations about sapphire-sapphire bonding will be required from the viewpoint

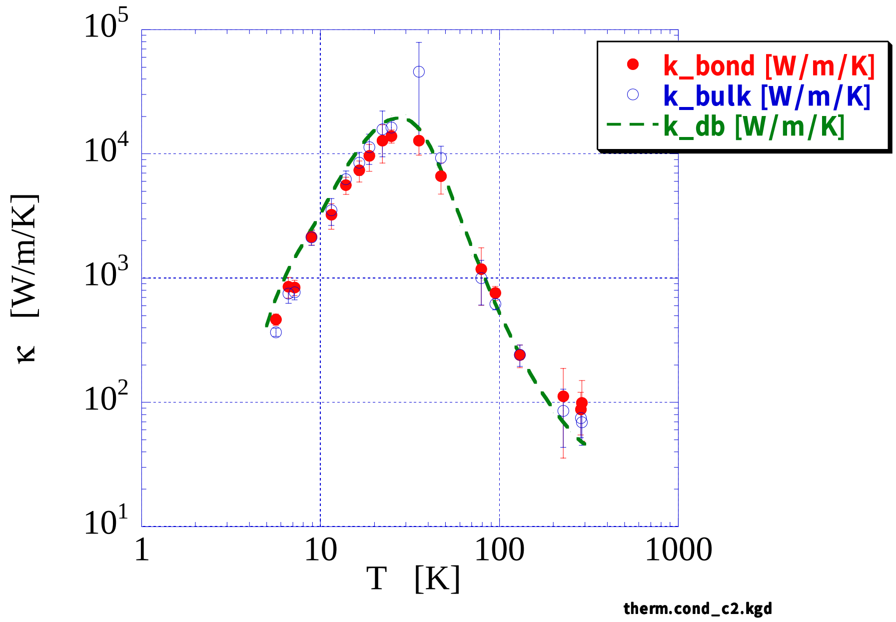

Fig. 2. Thermal conductivity of the sapphire bar with heat flow along c-axis. Solid circles show effective thermal conductivity of the section that contains a bonded interface. Normal circles show thermal conductivity of the specimen. Size of errors were evaluated from fluctuation of voltage readout of DMM. A broken line shows a published value of thermal conductivity for high-purity synthetic single crystal sapphire.

of mechanical loss and strength when we apply sapphire-sapphire bonding to the real LCGT.

GW=Gravitational Wave κ=Thermal Conductivity, W/m·K
LCGT=Large scale Cryogenic Gravitational wave Telescope
CGR=Carbon Glass Resistor T=Temperature, K
DMM=Digital MultiMeter

5. References

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