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Apparent Temperature Verses True Temperature of Silicon Crystals as a Function of Their Thickness Using Infrared Measurements

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Viewing the surface of objects subjected to high heat fluxes with an infrared camera or infrared sensor has proved to be a very effective method for monitoring the magnitude and distribution of surface temperatures on the object. This approach has been quite useful in studies of cooling silicon crystals in monochromators subject to high heat loads. The main drawback to this method is that single crystals of silicon are partially transparent to the infrared radiation monitored in most infrared cameras. This means that the infrared radiation emitted from the surface contains a component that comes from the interior of the crystal and that the intensity of the emitted radiation and thus the apparent temperature of the surface of the crystal depends on the thickness of the crystal and the kind of coating on the back (and/or the front) of the crystal. The apparent temperature of the crystal increases as the crystal is made thicker. A series of experiments were performed at Argonne National Laboratory to calibrate the apparent surface temperature of the crystal as measured with an infrared camera as a function of the crystal thickness and the type of coating (if any) on the back side of the crystal. A good reflecting surface on the back side of the crystal increases the apparent temperature of the crystal and simulates the response of a crystal twice the thickness. These measurements make it possible to interpret the infrared signals from cooled silicon crystals used in past high heat load experiments. A number of examples are given for data taken in synchrotron experiments with high intensity x-ray beams.

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INTRODUCTION

The very high intensity x-ray beams that will be present at the Advanced Photon Source and other third generation synchrotron sources will require that the first optical element in the beamline and, possibly, the second optical element as well, be cooled to remove the heat deposited by the x-ray beam.[1-3] In many of the beamlines this heat will be in the 1 to 5 kW range,[4] and any failure of the cooling system will require a quick response from safety control circuits to shut off the beam before damage is done to the optical element. In many cases, this first optical element will be a silicon diffraction crystal. Viewing the surface of objects subjected to high heat fluxes with an infrared camera or infrared sensor has proved to be a very effective method for monitoring the magnitude and distribution of surface temperatures on the object.[1,3] This approach has been quite useful in studies of cooling silicon crystals in monochromators subject to high heat loads. The main drawback to this method is that single crystals of silicon are partially transparent to the infrared radiation monitored in most infrared cameras. This means that the infrared radiation emitted from the surface contains a component that comes from the interior of the crystal and that the intensity of the emitted radiation and thus the apparent temperature of the surface of the crystal depends on the thickness of the crystal and the kind of coating on the back (and/or the front) of the crystal. The apparent temperature of the crystal increases as the crystal is made thicker.

A series of experiments were performed at Argonne National Laboratory to calibrate the apparent surface temperature of the crystal as measured with an infrared camera as a function of the crystal thickness and the type of coating (if any) on the back side of the crystal. A good reflecting surface on the back side of the crystal increases the apparent temperature of the crystal and simulates the response of a crystal twice the thickness. These measurements make it possible to interpret the infrared signals from cooled silicon crystals used in past high heat load experiments. This work has allowed one to go back and correct data taken in synchrotron experiments with high intensity x-ray beams and obtain better values for the temperature of the silicon crystals when experiencing high heat loads.

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup. An infrared (IR) camera was used to view a large single crystal of silicon that was shaped into vertical sections of different thickness (see figure 2) so that the IR camera viewed six different thicknesses of silicon at the same time. The temperature of the silicon crystal

was controlled with resistive heaters on the top and bottom of the silicon crystal. The heaters were shielded from the view of the IR camera. The apparent temperature of each thickness of silicon crystal was recorded as a function of the actual temperature of the silicon crystal as measured with two thermal couples mounted on the crystal. The apparent temperatures of the different thicknesses of silicon were compared to the background (room) temperature as measured with the IR camera. Each section of different thickness appeared to be uniform in apparent temperature as seen with the IR camera and the whole crystal was uniform in real temperature to within a degree as measured with the thermal couples. The thermocouples were read to the nearest 0.1 ^{o}C. One thermocouple was kept fixed near the center of the crystal. The other crystal was moved around on both the front and back of the crystal to check on the uniformity of the crystal temperature. The apparent temperatures were recorded by the infrared camera as a line trace of the temperature of the crystal in the horizontal direction. The apparent temperature readings were recorded to the nearest 0.1 ^{o}C. The data was taken from an average of 16 individual frames as recorded with the IR camera.

INFRARED MEASUREMENTS

The difference between the apparent silicon temperatures and the background temperature from the IR camera are plotted in figure 3 as a function of the thickness of the silicon. The dashed line in figure 3 is the actual temperature difference between the silicon crystal and the background temperature. The apparent temperature increases rapidly at first and then slowly approaches an equilibrium value near 80 percent of the real temperature difference of 27.8^{o}C The IR camera was set to assume that the object being viewed had an emissivity of 1.0. The equilibrium value of 80 percent is close to the transmission coefficient of the silicon-air interface.

One can calculate, to first order, the observed IR effective temperature by calculating the intensity of the radiation escaping from the surface relative to the IR radiation generated in the crystal.[4] Some of the various kinds of sequences of events over which one would have to integrate to obtain this average are shown in figure 4 for a simple slab of silicon If the absorption of the infrared radiation is quite low, as it is in silicon, then the photons can be reflected many times as they bounce back and forth between the front and back surface of the crystal. The general form of the equation for the radiation that escapes from the crystal is given by:

$$I(out) = I_0 T_0 (1-R) [1 + T^2 R^2 + T^4 R^4 + T^6 R^6 + ...] \quad (1)$$

where I_0 is the initial flux, T_0 is transmission fraction or one minus the absorption of the radiation as it travels from the origin of the radiation to the first surface that it encounters, T is the transmission fraction as the radiation travels from one surface to the next, and R is the reflection coefficient at the surface.[4] If the two absorption terms, T_0 and T, are so low that they can be ignored, then equation (1) becomes

$$I(out) = I_0 (1-R) [1 + R^2 + R^4 + R^6 + ...] \quad (2)$$

The reflection coefficient at these wavelengths is approximately 0.3. Substituting this value in equation (2) we have

$$I(out) = I_0 (0.7) [1 + 0.09 + 0.0081 + 0.00073 + ...] = 0.769 I_0. \quad (3)$$

If 10 percent of the radiation were to be absorbed on each pass through the crystal, $T = 0.9$ and $T_0 = 0.95$, then the value of I (out) would be slightly lower,

$$I(out) = I_0 (0.95) (0.7) [1 + 0.073 + 0.0053 + 0.00039] = 0.717 I_0. \quad (4)$$

This value comes quite close to the calibration value of 0.76 obtained with a 1.54-cm thick silicon crystal (see figure 3). To the first approximation, the effective emissivity of a thick crystal is equal to the transmission coefficient at the surface or (1-R).

Much work has been done at Argonne on the cooling of the first diffraction crystal in a two-crystal monochromator with liquid gallium. The gallium flows through channels just below the surface of the diffraction crystal. Thus, in order to interpret the data from this type of crystal, one needed to know what effect the layer of liquid gallium below the silicon would have on the apparent temperature of the silicon crystal. In a second experiment, part of the back side of each step of the silicon crystal was coated with liquid gallium. Two apparent temperatures were recorded for each thickness of the silicon crystal. The

temperature differences between these two sets of apparent temperatures and the background temperature are plotted in figure 5. The filled circles are the temperature differences for the case in which there is no gallium coating on the back surface of the silicon and the open squares are the temperature differences for the case in which there is a coating of liquid gallium on the back surface of the silicon. The real temperature difference between the silicon crystal and the background reference temperature was 19.4 ^{o}C for this experiment. The temperature differences for the gallium-coated case are systematically higher that the corresponding non-coated case. The apparent temperature differences from the IR camera for the gallium-coated case are similar to the apparent temperature differences observed for an uncoated silicon crystal 2.5 to 3 times as thick.

The presence of channels filled with gallium will complicate this analysis to some degree.[5] Figure 6 illustrates this complication. In practice, the gallium acts like a metallic, highly reflective surface and looks very similar to the sources near it. The reflection of the infrared radiation off the top of the gallium filled channel with raise the apparent temperature of this area as seen by the infrared camera. The ribs between the slots act like radiation traps in that the walls are coated with gallium and thus are highly reflecting, channeling the radiation down to the bottom of the rib. The bottom is coated with a layer of dye-attach paste that is a good radiator. This radiation plus the radiation from the silicon in the rib that is radiated upward will be reflected by the gallium at the walls of the rib and act as an additional source of IR radiation for the rib area. Figure 7 shows a line scan of the apparent temperature over a slotted crystal with gallium flowing in the slots, similar in geometry to the one shown in figure 6. The line scan was perpendicular to the direction of the slots. The slots were 0.80-0.90 mm wide and 3.4-3.3 mm deep. The ribs were 0.70-0.60 mm thick and the crystal thickness above the slots was 0.65-0.75 mm. The maximum variation in apparent temperature from slot area to rib area is 2.8^{o}C. The maximum come over the ribs where the apparent temperature is close to the apparent temperature of the unslotted crystal area. The minimums come over the gallium filled slots. Thus the contribution from the ribs is greater than the contribution from the reflection of the IR radiation from the reflection off the tops of the gallium filled slots. These data were taken with a Inframetrics 725 camera with the assumed emissivity set equal to unity.

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Figure Captions:

1. Schematic drawing of experimental setup. The silicon crystal is viewed from the common surface side for all the different thicknesses.

2. Cross section of the silicon crystal used in the temperature measurements. The crystal was viewed from the common face (bottom side in this figure) with the IR camera. The liquid gallium was placed on part of the surface of the stepped side of the silicon crystal.

3. The temperature difference between the room background temperature and the apparent temperature of the silicon as measured by the infrared camera, ΔT, in centigrade, is plotted verses the thickness of the silicon crystal. The camera assumed an emissivity = 1.0 in its calculation of the apparent temperature. The actual temperature difference between the silicon crystal and background room temperature was 27.8^{o}C.

4. Radiation from a uniform plate that is partially transparent to infrared radiation.

5. The temperature difference between background room temperature and the apparent temperature of the silicon crystal as measured by the IR camera, ΔT, in centigrade, is plotted verses the thickness of the silicon crystal. The filled circles are data for the case in which there is no coating on the back (stepped side) of the silicon crystal. The open squares are data for the case in which there is a liquid gallium coating on the back (stepped side) of the silicon crystal. The camera assumed an emissivity = 1.0 in its calculation of the apparent temperature. The actual temperature difference between the silicon crystal and background room temperature was 19.4^{o}C. Two sets of data are shown.

6. A line scan of the apparent temperature of a slotted crystal taken with the infrared camera perpendicular to the slot direction. The slots were 0.80-0.90 mm wide and 3.4-3.3 mm deep. The ribs were 0.70-0.60 mm thick and the crystal thickness above the slots was 0.65-0.75 mm.

7. Temperature profile perpendicular to cooling channels in the silicon crystal shown in figure 6 with gallium flowing in the slots. Only the slotted portion of the crystal is shown.

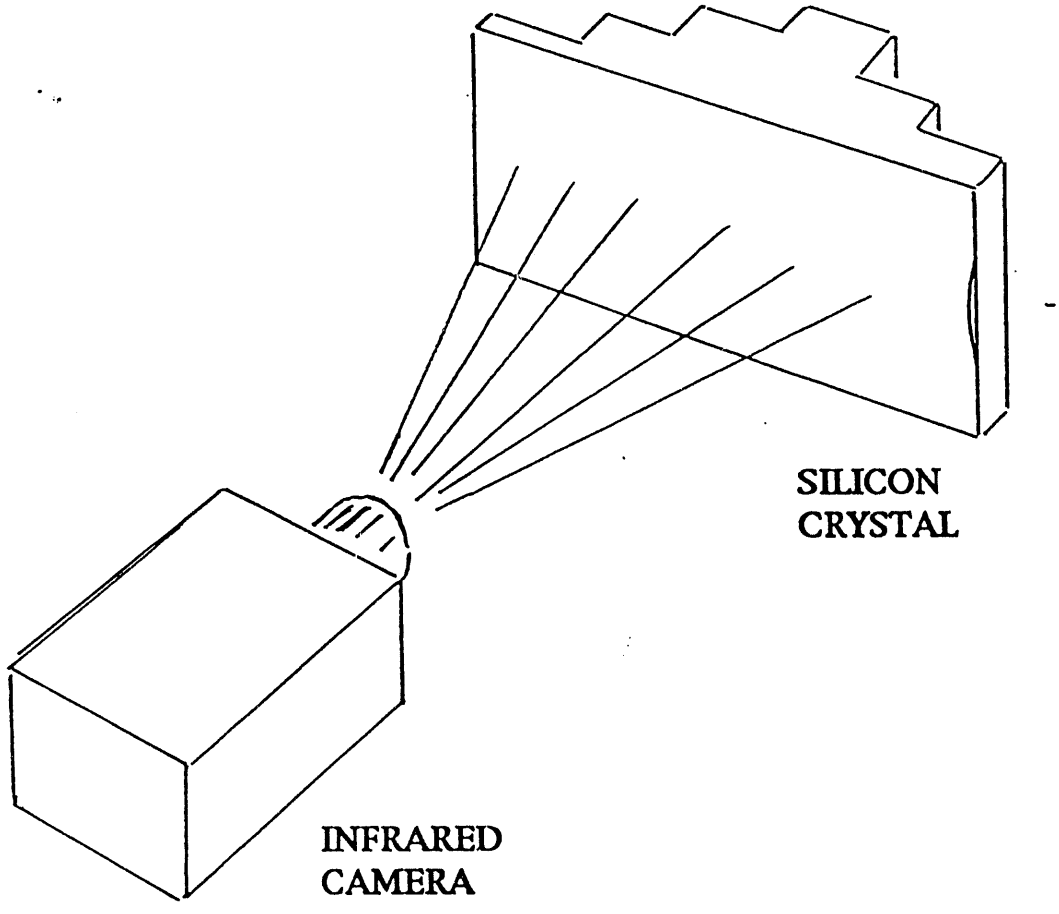


Fig 1

CROSS SECTION OF THE SILICON CRYSTAL

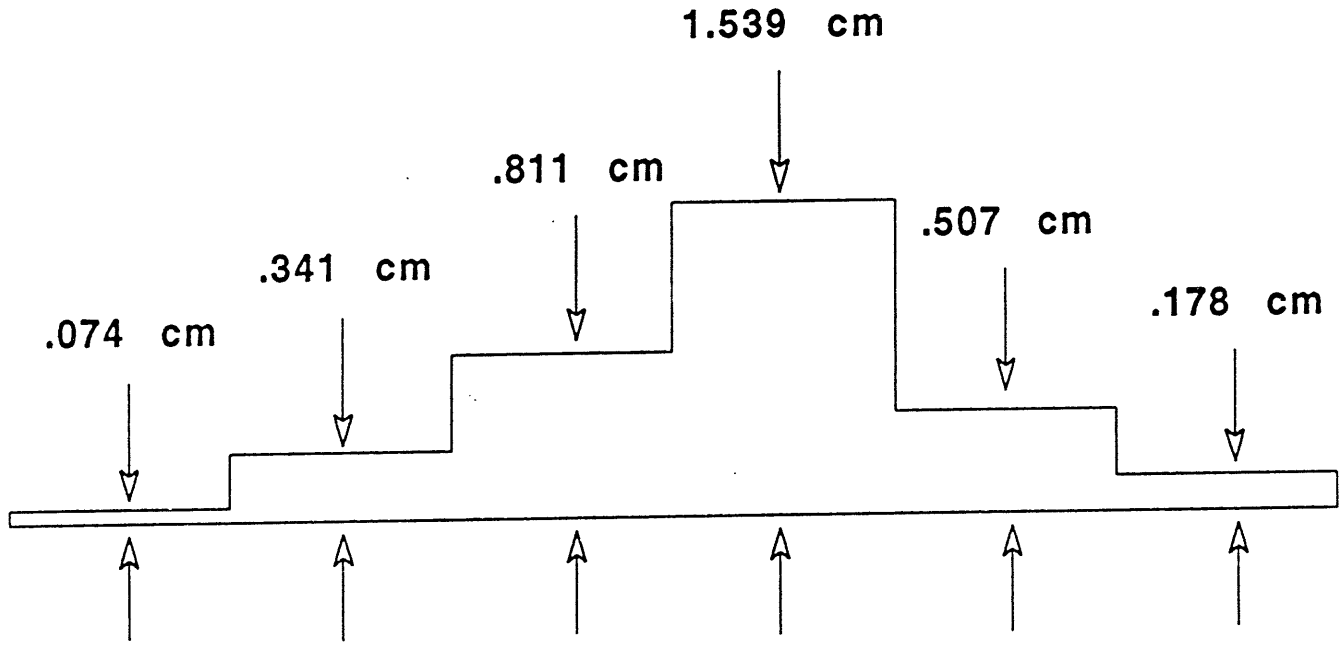


Fig 2

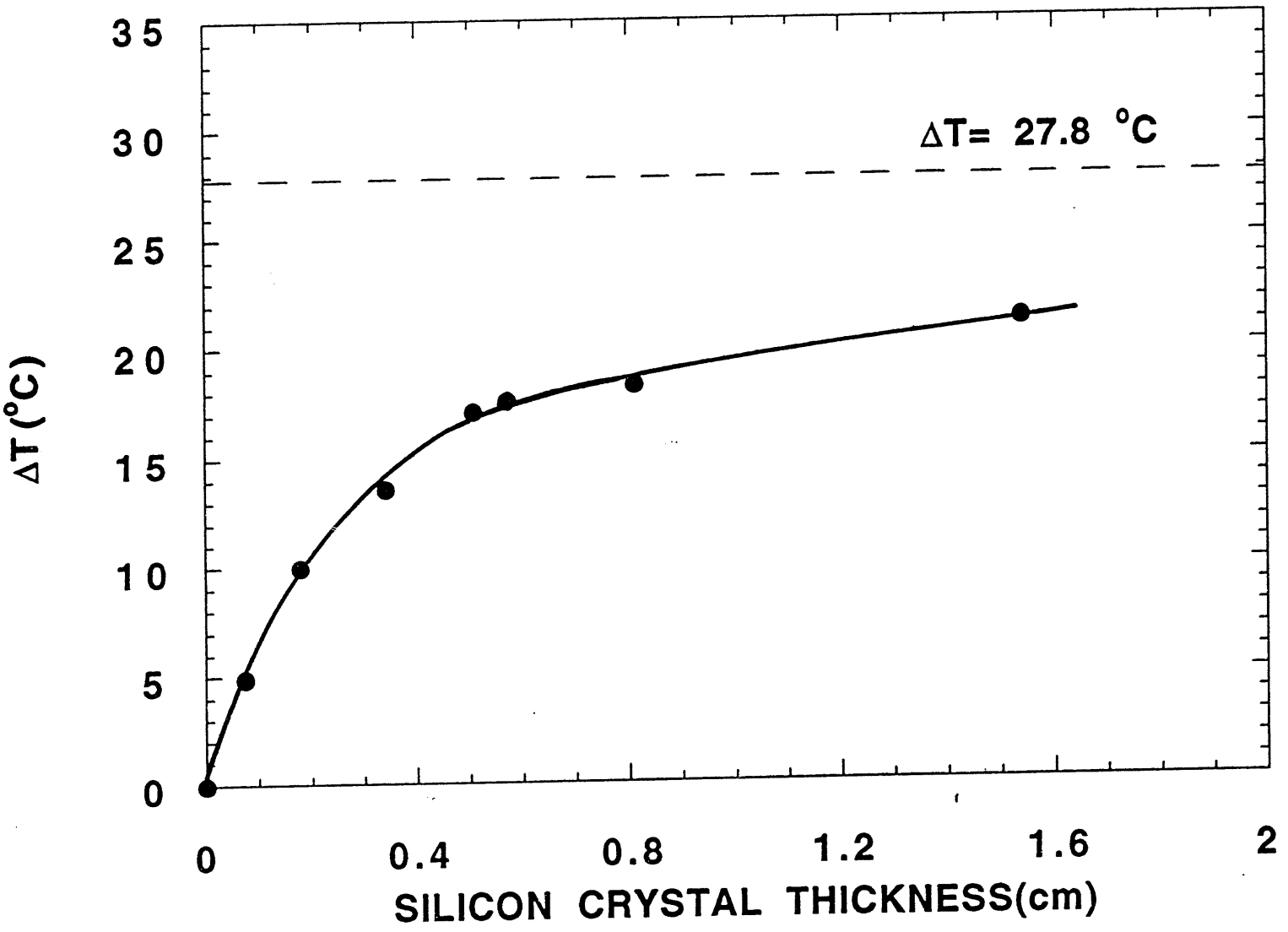

35
30
25
20
15
10
5
0
ΔT (°C)
ΔT= 27.8 °C
0
0.4
0.8
1.2
1.6
2
SILICON CRYSTAL THICKNESS(cm)

Fig 3

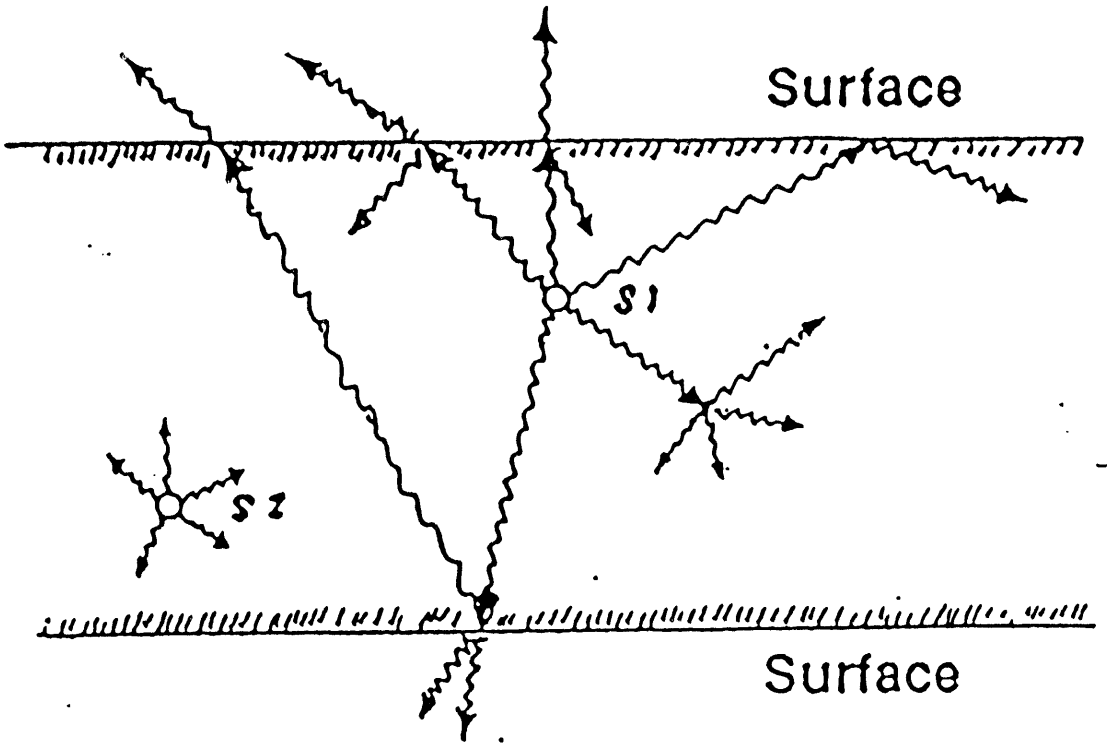
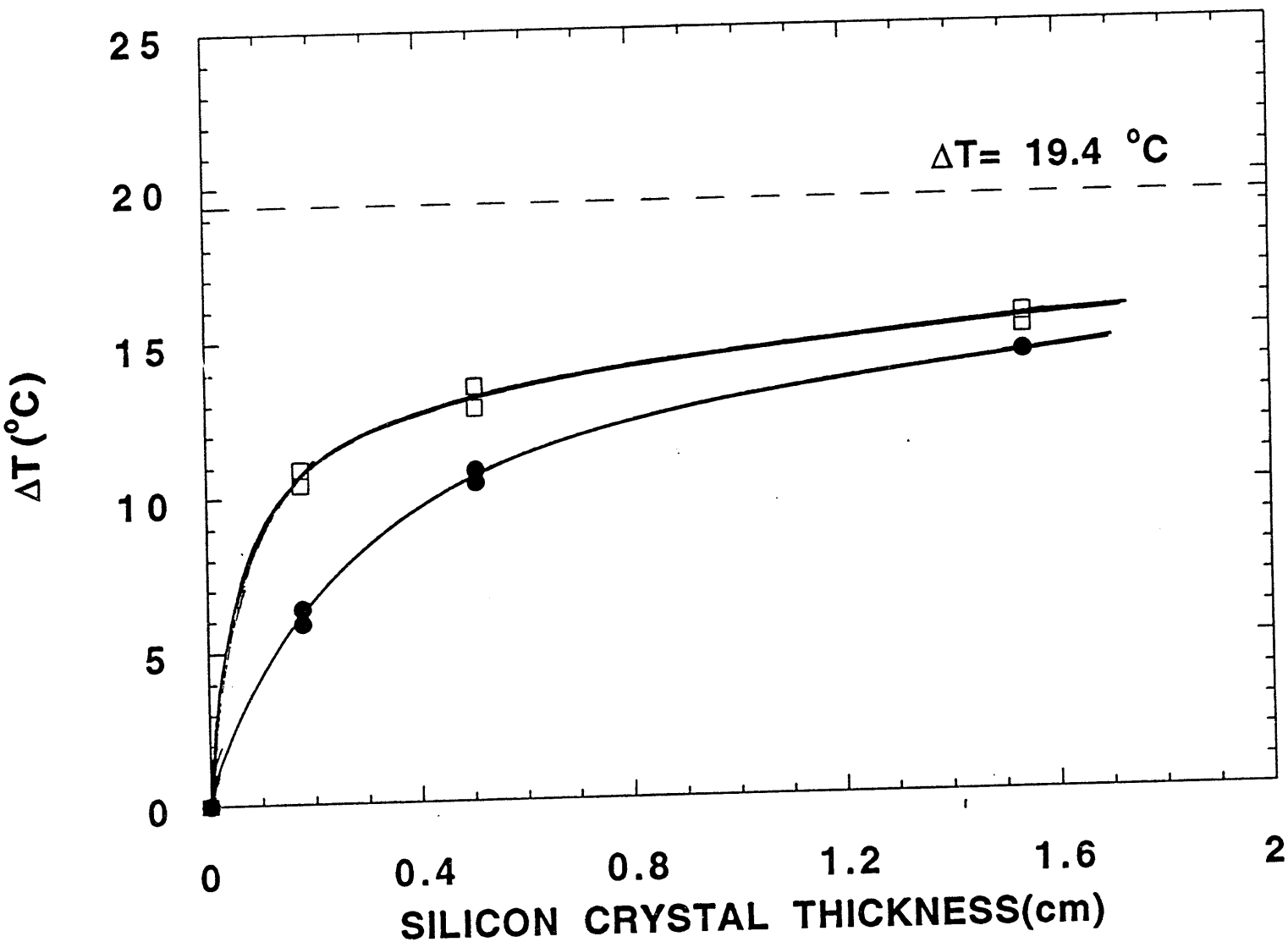


Fig 4


ΔT= 19.4 °C
ΔT (°C)
25
20
15
10
5
0
0
0.4
0.8
1.2
1.6
2
SILICON CRYSTAL THICKNESS(cm)

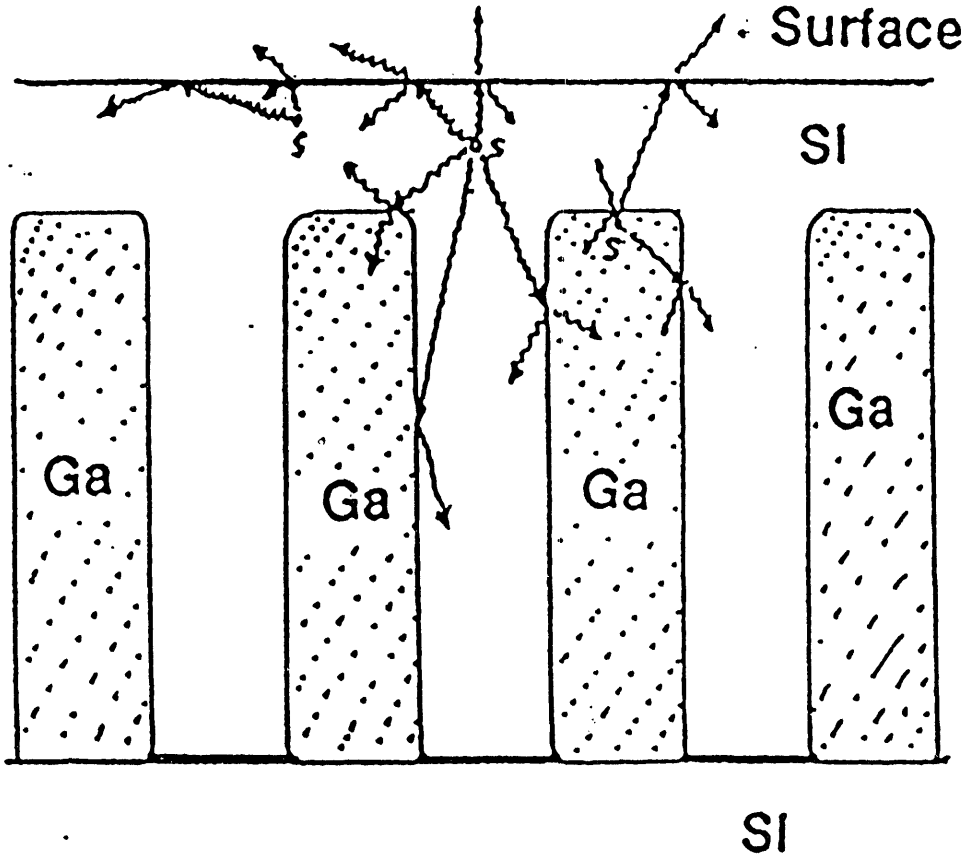


Fig 6

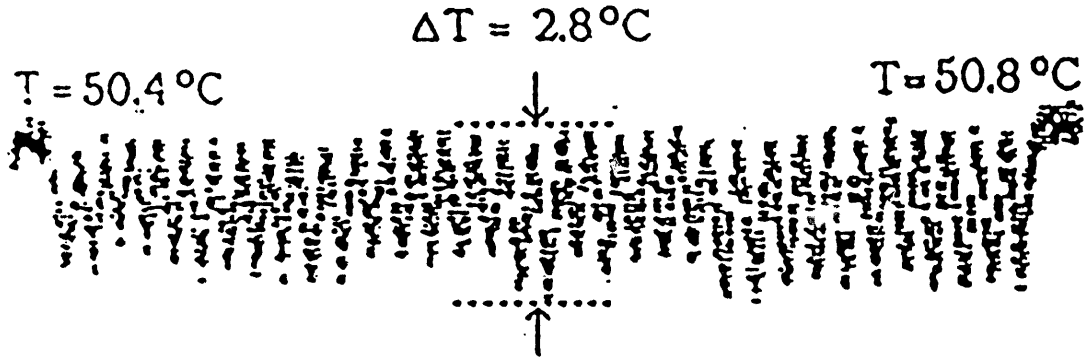


Fig 7

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