DIELECTRIC BEHAVIOR OF SEMICONDUCTORS AT MICROWAVE FREQUENCIES

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KEY WORDS

Semiconductors; frequency shift; Q-change; dielectric relaxation, microwave resonant signal.

OBJECTIVES

1. To learn about the components of a microwave spectrometer.

2. To learn to operate the spectrometer.

3. To understand the shape of the signal and record data in terms of frequency shifts and Q-changes.

4. To understand the dielectric properties of semiconductors: germanium and silicon.

SUMMARY

A cylindrical microwave resonant cavity in TE_{011} mode is used to study the dielectric relaxation in germanium and silicon. The samples of these semiconductors are used to perturb the electric field in the cavity and Slater's perturbation equations are used to calculate the real and imaginary parts of the dielectric constant. The dielectric loss of germanium and silicon is studied at different temperatures and Debye's equations are used to calculate the relaxation time at these temperatures.

INTRODUCTION

A number of experiments have been performed to investigate the dielectric properties of solids, liquids and gases at various frequencies (ref. 1-6). The present experiment is to study the dielectric relaxation mechanism in germanium and silicon.

The microwave resonant technique has been used by several investigators in the past and it has become a standard technique to study the dielectric behavior in various compounds of interest. Hong and Roberts (ref. 7) used a cylindrical cavity in TM_{010} mode to study the dielectric properties of solids and liquids. Dahiya et al. (ref. 8-10) used a microwave resonant cavity to study dielectric relaxation mechanism in various polar and non polar compounds.

It has proven to be a very interesting experiment to find the dielectric response of a material near a phase transition region, i.e., going from an ordered to a disordered phase. From measurements of the static dielectric constant of compounds as a function of the temperature, important conclusions concerning molecular freedom may be drawn. The dielectric response of a polar liquid shows a large change at the freezing point. A typical example is that of water as studied by Dahiya et al. (ref. 8). The drop in the dielectric constant of water at the freezing point is caused by the partial or complete loss of rotational polarization (freedom to reorient), while the electronic and vibrational polarizations remain relatively unchanged.

In the present investigation, dielectric behavior of semiconductors, germanium and silicon were studied at different temperatures. The sample under investigation was placed along the vertical axis of the cavity. The sample was taken in a capillary tube and the thermocouple leads were inserted into the capillary tube to make a fine contact with the sample. The sample was then cooled by flushing cold nitrogen gas around the cavity and desired temperature was obtained. The temperature was then allowed to vary in small steps and frequency shifts and Q-changes were recorded.

EQUIPMENT CONFIGURATION AND THEORY

The block diagram of the microwave spectrometer used in this investigation is shown in Figure 1 that shows all the components needed to study the dielectric relaxation mechanism. The source of the microwaves was a 2K25 tunable klystron made by Western Electric. The frequency produced by the klystron varies between 8.8 to 11.0 GHz. The klystron was powered by a Hewlett Packard 715A power supply. The microwaves produced by the klystron were guided by waveguides in the x-band of frequency. The signal reaching the directional coupler was divided into two parts. A part of this signal reaches the microwave resonant cavity via an attenuator and a wavemeter. The attenuator was used to adjust the right amount of microwave power for the sample being studied. The function of the wavemeter is to determine the exact frequency of the klystron by tuning it to the resonant frequency of the klystron.

The next important device in this operation is a crystal detector which is used for the radio frequency wave. Crystal detectors have wide use in the microwave field because of their sensitivity and simplicity. They are used as "video detectors" to provide either a dc output when unmodulated microwave energy is applied, or a low frequency ac output when the microwave signal is modulated. The essential parts of a crystal detector are a semiconducting wafer and a metal "whisker" which contacts the wafer. In the present experiment two such crystal detectors were used, one of which was installed in the reflectometer to provide dc output when the klystron modulated signal is reflected from the resonant cavity. Another crystal detector was mounted in a directional coupler to mix the modulated klystron signal with the nth harmonic waves from the standard frequency multiplier.

The purpose of modulating the microwave signal was as follows. The unmodulated signal from the klystron gives a very narrow frequency interval as shown in the microwave power vs frequency curve in Figure 2a. With a signal like that it is very difficult to measure the shifts in frequencies and the Q-changes of the signal. An oscilloscope horizontal sawtooth sweep voltage was applied to the repeller of the klystron. This voltage was derived from the time base of a Tektronix model 533A dual channel oscilloscope that sweeps the klystron over the range of frequencies desired while simultaneously a chopper signal of 31 kHz was impressed upon the klystron repeller electrode to produce an ac signal of that frequency at the detector. The modulated signal is shown in Figure 2b and Figure 2c shows the reflected power absorption by the resonant cavity. As shown in Figures 3a and 3b, the power absorption by the cavity was modulated to give a differential display of the resonance profile in the form of a butterfly. Figures 3c and 3d show the modulated signal before the sample under investigation was introduced into the cavity and after the sample had been introduced respectively. The resonance frequency shifted and the width of the signal changed as seen in Figure 3d. The modulated signal was amplified by a pre-amplifier and displayed on the oscilloscope.

Through the Webster G40P5158 directional coupler, a part of the microwave signal was mixed with a standard frequency obtained from a Hewlett Packard 612A UHF signal generator. A Kenwood R-1000 radio receiver was used to detect the frequency difference between the klystron resonant frequency and the standard frequency source. The resulting frequency difference yielded two markers which were displayed on the oscilloscope. These markers were used to record the frequency shifts and the Q-changes of the resonant signal as the cavity was loaded with the sample under investigation.

A cylindrical cavity in the TE_{011} mode was designed. A long copper coil was wrapped around the cavity and the cavity placed in a thermal bath. As the sample under investigation is introduced into the cavity it perturbs the electric field of the cavity and as a result of that the resonant frequency shifts and the Q of the cavity changes. The frequency shifts and Q-changes of the signal are related to the real and imaginary parts of the dielectric constant through the Slater's perturbation equations as follows. (ref. 8)

$$\frac{\Delta f}{f_o} = -\frac{\epsilon' - 1}{2} \frac{\int \vec{E}_s \cdot \vec{E}\, dv}{\int \vec{E} \cdot \vec{E}_a\, dV} \tag{1}$$

$$and\ \Delta\left(\frac{1}{Q}\right) = \epsilon'' \frac{\int \vec{E}_s \cdot \vec{E}\, dv}{\int \vec{E} \cdot \vec{E}_a\, dV} \tag{2}$$

where $\vec{E}$ is the field of the unperturbed cavity, E_a is the microwave field as applied to the cavity and E_s is the field of the sample itself, and v and V are the volumes of the sample and cavity respectively.

The signal Q-change is further related to the width of the signal by

$$\Delta\left(\frac{1}{Q}\right) = \frac{\sqrt{3}\,\Delta W}{f_o} \tag{3}$$

where f_0 is the resonant frequency of the system and W is the frequency separation in Hertz of the resonance half-power points.

The real and imaginary parts of the dielectric constant ϵ' and ϵ'' are further related to the relaxation time (τ) using Debye's equations (ref. 11) as follows.

$$\frac{\epsilon_s - \epsilon'}{\epsilon''} = \omega\tau \tag{4}$$

where $\omega = 2\pi f_0$, and ϵ_s is the value of the dielectric permittivity for a static field.

PROCEDURE

The sample under investigation was taken in a fine capillary tube. A thermocouple was inserted into the tube to make a fine contact with the sample inside the tube. The capillary tube was then inserted into the microwave resonant cavity along the symmetry axis of the cavity to ensure a sizeable perturbation of the microwave resonant signal. The thermocouple was inserted into the capillary tube to ensure it was making a fine contact with the sample inside that tube. The initial readings of the temperature, and microwave frequency were recorded. The cavity was then cooled to the desired temperature by circulating cold nitrogen gas through the copper tube wrapped around the cavity. The system was then allowed to warm and the readings were taken by adjusting the markers on the center and left and right peaks of the microwave resonant signal. These readings were taken at an interval of 1°C till the desired temperature of the system was achieved. At each reading, sufficient time was allowed to elapse so that the sample and resonant cavity came to thermal equilibrium.

RESULTS AND CONCLUSION

The frequency shifts and the width changes of the microwave resonant signal for the semiconductors germanium and silicon were calculated by using Slater's perturbation equations 1 and 2 in a computer program written for microwave spectroscopy studies. As seen from these equations, the frequency shifts and the width changes are related to the real and the imaginary parts of the complex dielectric constant. Figures 4 and 5 show the behavior of Q-changes of the signal ($\Delta(1/Q)$) and frequency shifts ($\Delta f/f_0$) as a function of temperature. As seen in Figure 5, the frequency shift increases with temperature with its minimum value at 84.8 K. Smakula et al. (Ref. 12) studied the dielectric behavior of this semiconductor at very low temperature and it seemed to have another minimum around 4 K. Figure 4 shows a similar behavior of the Q-change with a minimum value around 84.8 K and a maximum value around 196 K and it decreases as the temperature increases up to 300 K. The low temperature studies of this material indicate another maximum around 10 K as shown by Smakula et al. (Ref. 12). Figures 6 and 7 show behavior of Q-change and the frequency shift for silicon between 70 K and 300 K. The relaxation times for these semiconductors were calculated using equation 4 and were of the order of 10^{-11}-10^{-14} sec.

The bound electrons and the free carriers in a semiconductor material account for the dielectric permittivity and the conductivity of the material. The bound electrons in the semiconductor can be categorized as the core electrons of the materials, the valence electrons, and the electrons from the impurity atoms. The valence electrons and the core electrons have excitations in the infrared frequency regions. The permittivity of these electrons may not have any imaginary term and these electrons do not show any temperature dependence at very low temperature. However, the impurity electrons vary with temperature and thus affect the complex permittivity or the dielectric constant of the material.

In this investigation, a microwave spectrometer was assembled to study the dielectric relaxation in various compounds of interest. The spectrometer was designed to study these behaviors at very low temperatures. The technique was very successful in monitoring the dielectric behavior of germanium and silicon. The main emphasis of this research was to create an advanced physics laboratory experiment in which undergraduate students were involved to design the spectrometer piece by piece. The spectrometer was then used as a tool to study the dielectric behavior of various polar and nonpolar compounds. Semiconductors germanium and silicon were chosen for their dielectric behavior at low temperatures. The cooling system used in the microwave spectrometer was also designed by undergraduate students and was very efficient.

The main purpose of this experiment was to understand the function of each component of the microwave spectrometer and to use it as a technique to monitor the dielectric behavior in semiconductors germanium and silicon at low temperatures. The detailed results of the dielectric relaxation in these semiconductors will be presented elsewhere as a continuation of this experiment.

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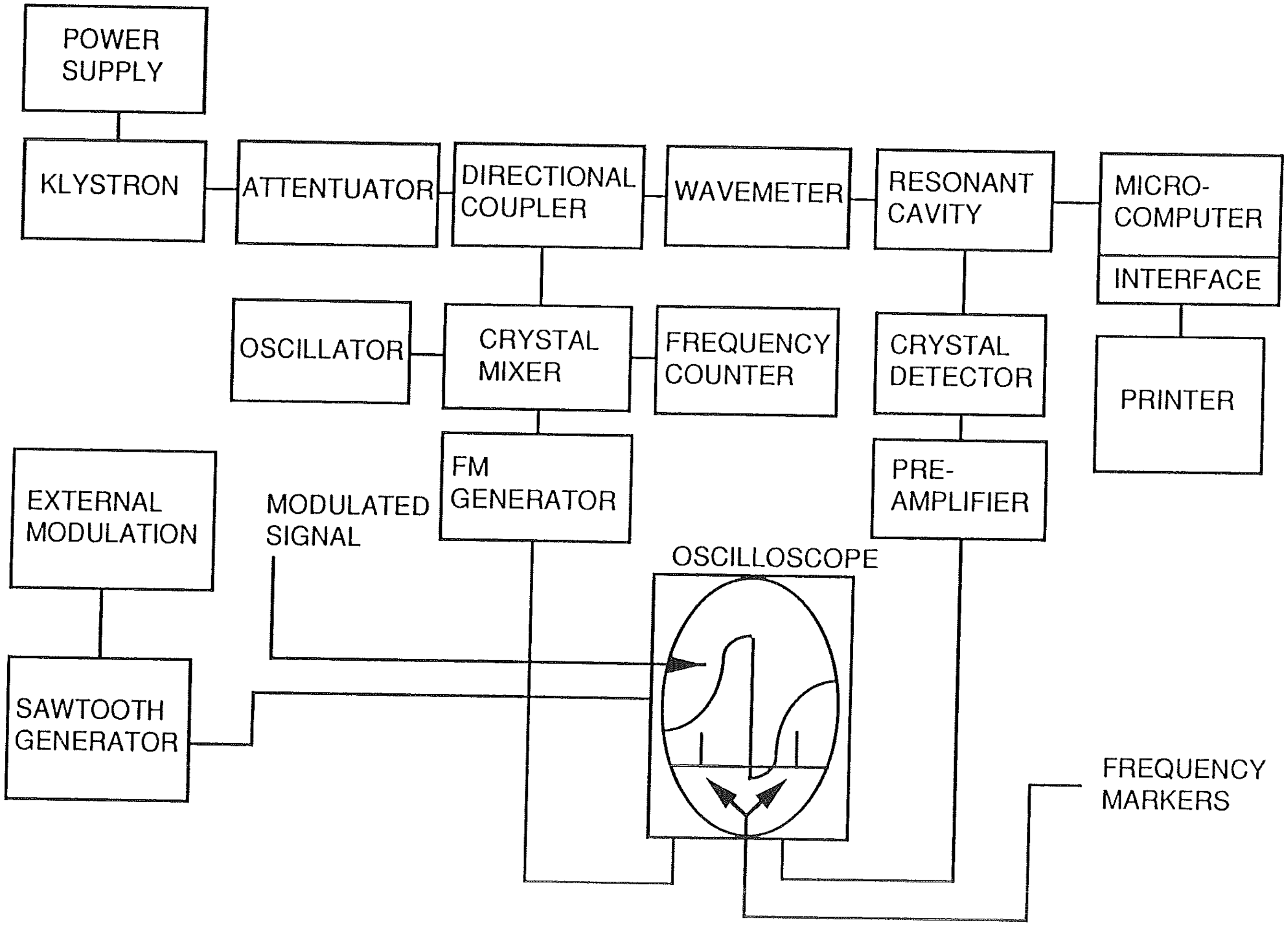
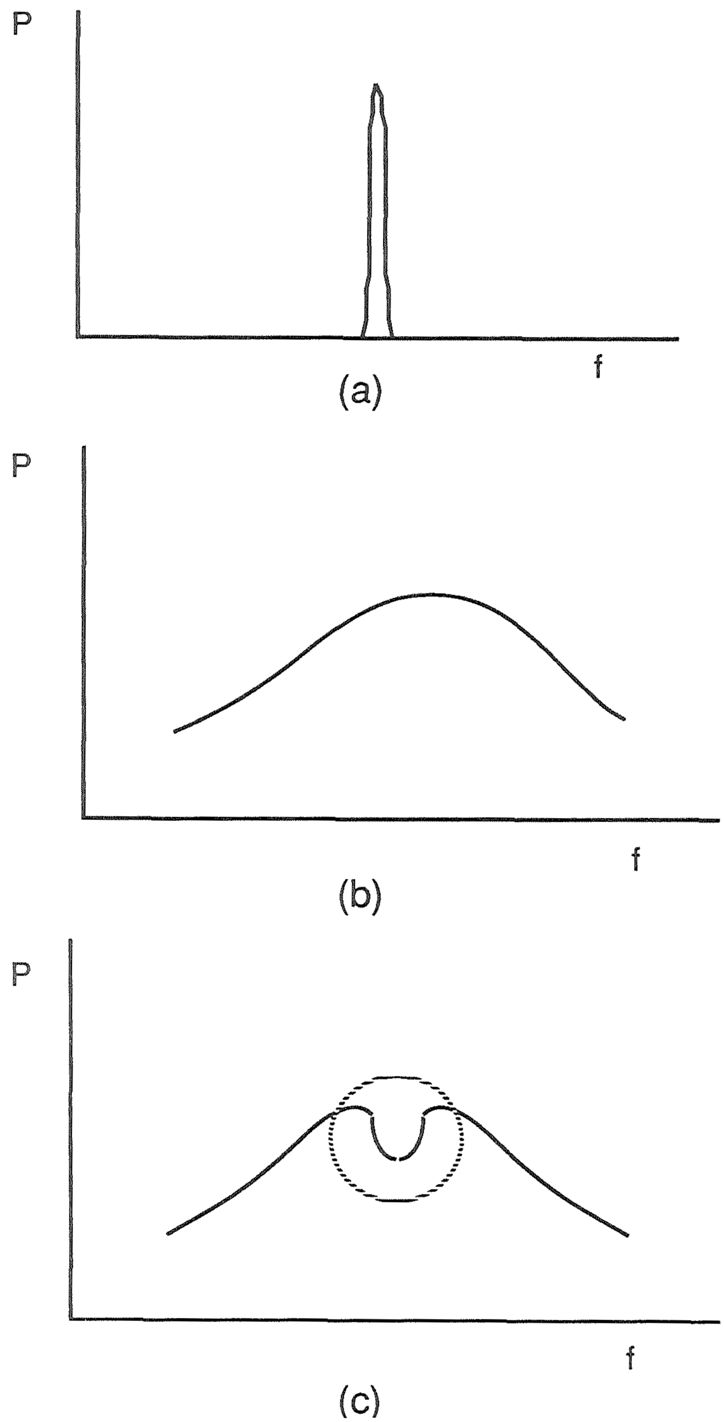
1. Block diagram of the microwave spectrometer used in this investigation.

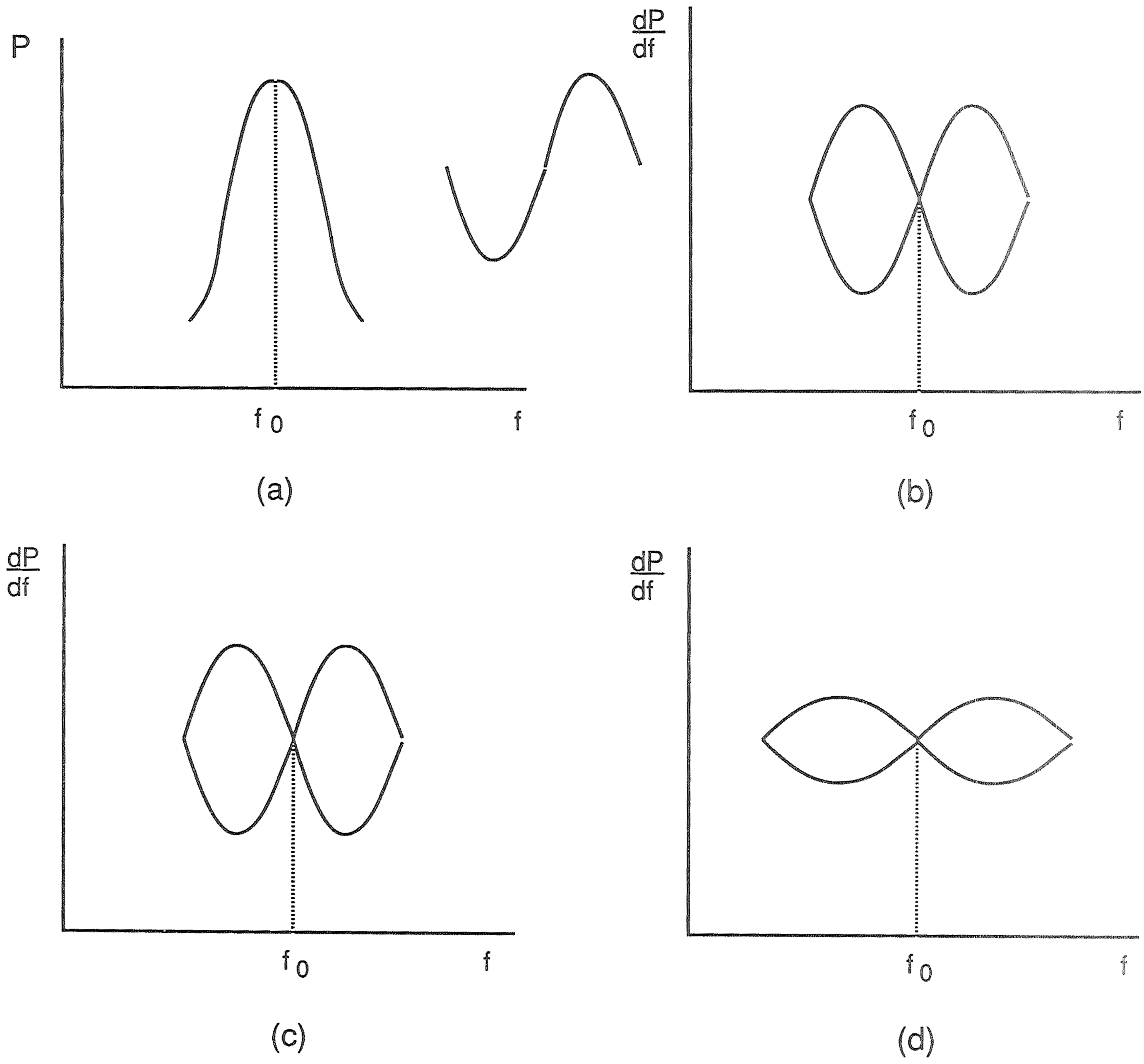




2. (a) Klystron mode shape (unmodulated width).

(b) Klystron mode shape (modulated width).

(c) Reflected power absorption by cavity.

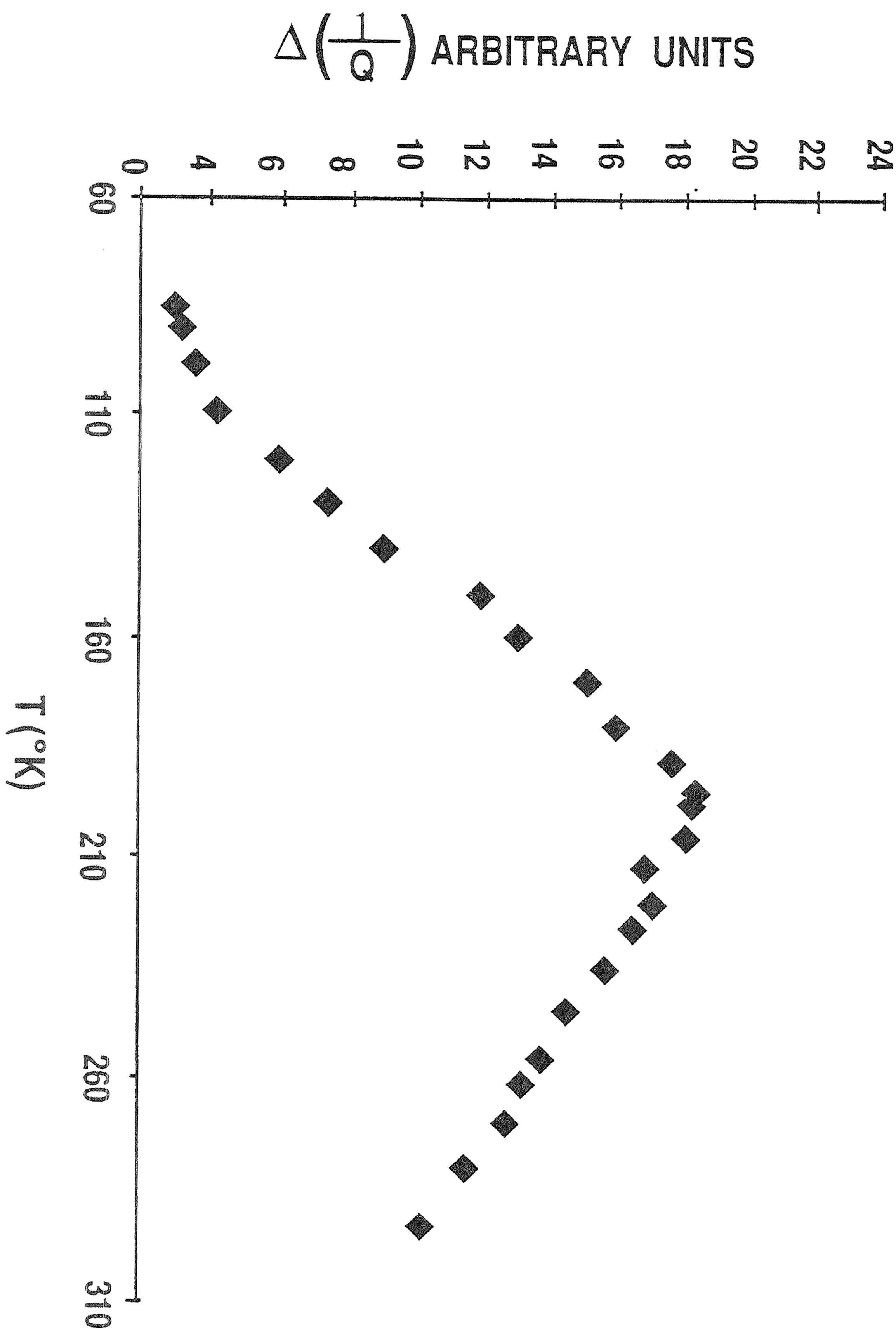


3. (a) Enlarged drawing for power absorption by the cavity.

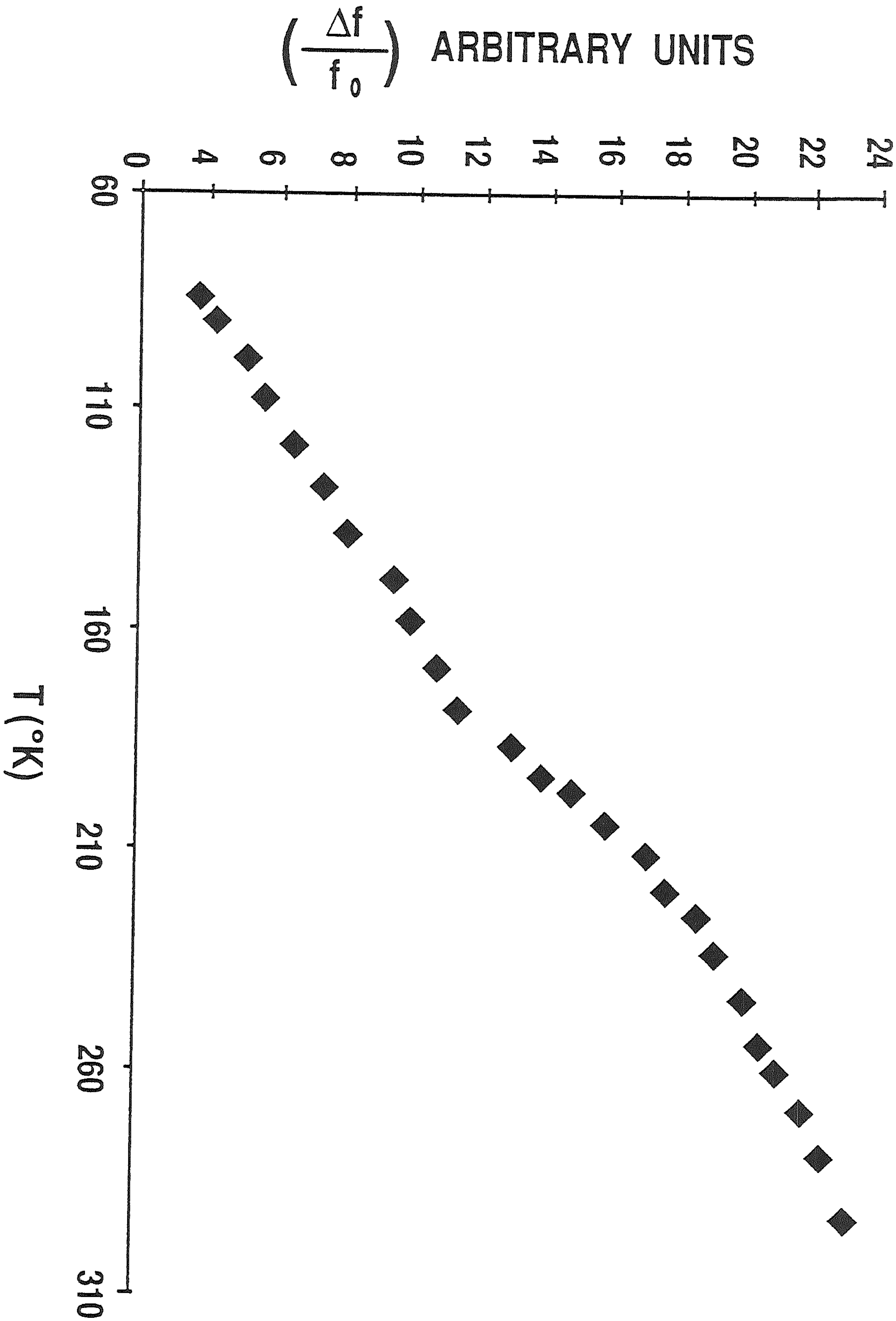
   (b) First derivative of resonance absorption.

   (c) Resonance absorption signal (unperturbed).

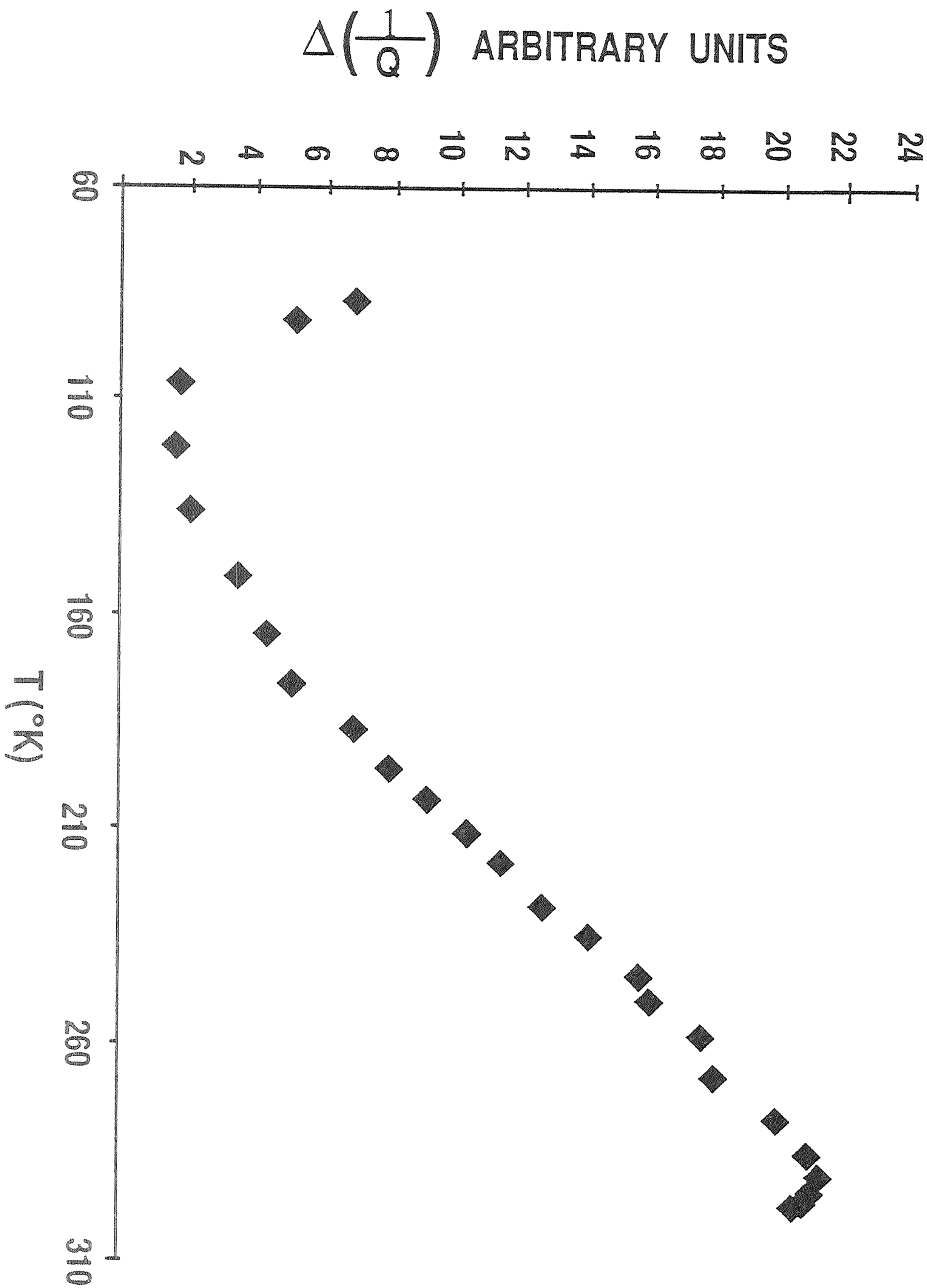
   (d) Resonant frequency shift and width change due to insertion of the sample into the cavity.



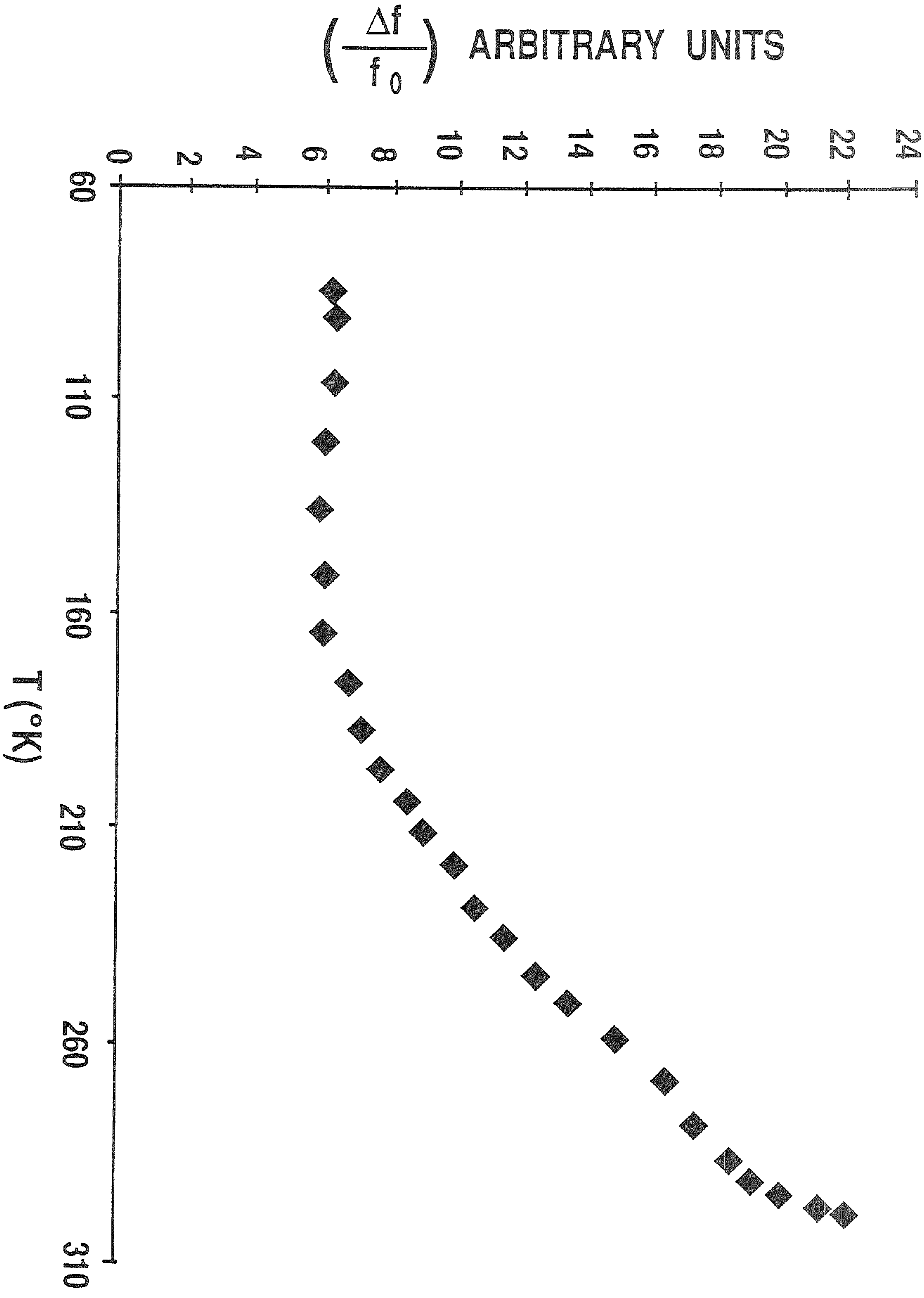
4. Microwave loss Δ(1/Q) as a function of temperature for a sample of semiconductor germanium.



5. Frequency shift $\Delta f/f_0$ as a function of temperature for a sample of semiconductor germanium.



6. Microwave loss Δ(1/Q) as a function of temperature for a sample of semiconductor silicon.



7. Frequency shift $\Delta f/f_0$ as a function of temperature for a sample of semiconductor silicon.