A LAMB WAVE TEMPERATURE SENSOR FOR SEMICONDUCTOR WAFER PROCESSING

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INTRODUCTION

Molecular Beam Epitaxy (MBE) technology is now being used to engineer many optoelectric devices. Future devices of interest include those based on quantum well structures such as resonant tunneling diodes, multistate memory and optical modulators. These devices exploit multilayer structures based on InGaAs/AlAs, InAs/GaSb/AlSb, InAs/GaAs, etc. Their performance exhibits extreme sensitivity to the quality and composition of the individual epitaxial layers of the multilayer structures. The quality of the deposited films (and thus the yield/ performance of devices) is believed to be quite sensitive to the temperature of the semiconductor substrate upon which epitaxial film growth occurs. Recently it has been shown that significant substrate temperature changes accompany the growth of semiconductor films on semiconductor wafers [1]. These cannot be easily detected by either conventional thermocouples (because they are only weakly thermally coupled to the substrates), or optical radiometric methods which encounter difficulties in the MBE environment due to stray light, variations in window transmissivity, changes to the sample’s emissivity during film growth, etc. Thus today, there exists a need for sensors that are able to measure, without perturbation to the epitaxial growth process, the substrate temperature during MBE growth.

Ultrasonic velocity is well known to be a function of temperature for most materials. It results from the softening of a material’s elastic constants with increasing temperature. It has been used to infer the internal temperature of primary metals [2], and has been proposed as a
means of silicon wafer temperature determination during rapid thermal annealing [3]. The basic idea is that by measuring the variation of velocity as a function temperature, a test sample can in effect be used as its own thermometer. It appears to be a particularly promising approach for semiconductor wafers because of their reproducible composition and orientations (factors which can also effect velocity and thus give anomalous temperature indications). The impediments to its application for MBE are the need to work with a rotating substrate in an ultrahigh vacuum, ultra high purity environment and the anisotropic, single crystal nature of the wafer. The environment precludes the use of contact ultrasonic approaches. One possible solution is to use a pulse laser ultrasonic excitation of the wafer and to detect ultrasound (after propagation across the wafer) with a laser interferometer [4], both located outside the MBE machine. The second problem requires a careful analysis of ultrasonic propagation in anisotropic plates.

The substrates upon which epitaxial growth is performed are all relatively thin (~ 0.5 mm). Thus, for most of the ultrasonic frequency components in the laser excited source, the motion of one substrate surface inevitably interacts with that on the other surface, and the dominant ultrasonic modes that propagate across the diameter of the wafer are Lamb wave modes. Lamb waves are well known to be dispersive, which present a potentially severe problem for the time of flight method normally used with the "pulsed" laser technique [2]. The "pulsed" laser signals have a broad frequency spectrum and thus an ill defined time of flight. Many researchers in the past have tried to use the lowest order symmetric mode to determine the elastic moduli of materials [5,6], because this mode is less dispersive. However, it is only weakly excited by a laser source and usually has a very small amplitude, making it still difficult to pinpoint its arrival. On the other hand, the lowest antisymmetric mode usually has a large amplitude and often dominates the laser generated wave form, but it is highly dispersive. Because of its strong dispersive behavior signal analysis methods are required to determine its phase velocity as a function of frequency [7].

Here, we first show how to calculate dispersion curves for antisymmetric wave modes in the [100] and [110] directions of cubic single crystal wafers at low frequencies. We have generated and measured Lamb waves in Si substrates using optical methods over a range of different temperatures. The phase velocity as a function of frequency for the lowest antisymmetric Lamb mode has been obtained using a digital signal processing method [7,8], and the velocity as a function of temperature at fixed frequencies deduced.

LAMB WAVE PROPAGATION IN CUBIC CRYSTAL SUBSTRATES

Many semiconductor materials used for MBE have a cubic crystal structure. Consider a cubic substrate wafer material whose surface normal is in the [001] direction. Let the $x_1$, $x_2$, and $x_3$ coordinates coincide with the [100], [010], and [001] directions, respectively. Then, the dispersion equation
for Lamb waves in either the [100] or [110] direction at low frequencies can be shown [9] to be given by:

$$\frac{\text{Tan}(kq_1 h)}{\text{Tan}(kq_2 h)} = \left[ \frac{q_2 (g_1 q_2^2 - p^2 - g_2) (g_1 q_2^2 + g_2 p^2 - g_2)}{q_1 (g_1 q_1^2 - p^2 - g_2) (g_1 q_1^2 + g_2 p^2 - g_2)} \right]^{\pm 1}$$

(1)

where the plus and minus signs hold for either the antisymmetric or symmetric Lamb modes respectively, $g_1 = c_{11}/c_{44}$, $g_2 = c_{12}/c_{44}$, $c_{11}$, $c_{12}$ and $c_{44}$ are elastic constants, $k = 2\pi/\lambda$ is the wavenumber, $\lambda$ is the wavelength in the propagation direction, $kq_1$ and $kq_2$ are wavenumbers in the $x_3$ direction, $f$ is the frequency of ultrasound, $2h$ is the substrate thickness, $p = v/\sqrt{c_{44}/\rho}$ is a dimensionless velocity, $v$ is the Lamb mode phase velocity in the propagation direction, and $\rho$ is the substrate density. The quantities $q_1$ and $q_2$ are given by:

$$q_1^2 = -b \pm \sqrt{b^2 - 4ac}$$

$$q_2 = \frac{2a}{2a}$$

(2)

where for the [100] direction:

$$a = g_1, \quad b = g_1^2 - g_2^2 - 2g_2 - (1+g_1)p^2, \quad c = (g_1 - p^2)(1-p^2)$$

(3a,b,c)

while for the [110] direction:

$$a = g_1, \quad b = 1 - p^2 + g_1 \left( \frac{2 + g_1 + g_2}{2} - p^2 \right) - (1+g_2)^2,$$

$$c = \left( \frac{2 + g_1 + g_2}{2} - p^2 \right)(1-p^2),$$

(4a,b,c)

Laser generated ultrasound is composed of a broad spectrum of frequencies. When Lamb wave modes are generated by a laser source, the received signal must contain many symmetric and antisymmetric wave modes. But the problem is simplified if the propagation distance is sufficiently long that high frequency components are attenuated, and the different modes become well separated in arrival time. After low pass filtering, only the lowest order modes need to be considered. Fig. 1 shows dispersion curves for the lowest antisymmetric mode of a Si wafer, where (at 20°C) $c_{11} = 160.1$ GPa, $c_{12} = 57.8$ GPa, $c_{44} = 80.0$ GPa, $\rho = 2.332$ g/mm$^3$ [10]. The velocity in the highest velocity [110] direction and the lowest velocity [100] direction are both shown. The small difference in velocity between the two
Fig. 1  Dispersion curves for the lowest antisymmetric mode of a Si wafer.

Fig. 2  Experimental setup used to explore ultrasonic temperature sensing of Si wafers.
directions suggests that velocity measurements based on the lowest antisymmetric mode can tolerate uncertainty in the propagation direction, only a few random orientation measurements would be needed to obtain a good "orientation average" velocity.

EXPERIMENTAL RESULTS AND DISCUSSION

To test the approach, ultrasonic velocity measurements have been conducted on Si substrates, Fig. 2. The substrates were 50.8 mm in diameter, and 0.6 mm in thickness. A Q-switched Nd:YAG laser, operated at a 50mJ energy level, generated Lamb waves at the edge of the substrates, and the out-of-plane displacement was detected by an interferometer that was driven by an Argon ion laser. Source-to-receiver distances were 43 mm. The samples were heated radiatively from underneath, while the lasers were directed at the surface from above. The substrate temperature was measured by a thermocouple (±2°C accuracy) attached to the surface of the wafer. Measurements were made in the [110] direction from ambient temperature up to 310°C.

Fig. 3 shows a recorded waveform measured at 105 °C. The waveform contains many wave modes. It can be seen from Fig. 3 that the first arrival of the lowest symmetric mode is difficult to pinpoint, whereas the lowest antisymmetric mode is the dominant feature of the waveform.

![Waveform](image)

**Fig. 3** A typical waveform measured for a single Si wafer at 105 °C.
A low pass Kaiser window [11] with a 1 MHz cut-off frequency was first applied to the received signals to remove high frequency signal components and noise. The velocity for the lowest antisymmetric mode was determined using a digital signal processing method [7,9] suitable for dispersive waves. The process was repeated for signals measured at several different temperatures. A typical result is shown in Fig. 4 for the signal measured at 105 °C. A possible reason for the scatter in data is that the propagation distance was insufficient to fully separate Lamb modes that the lowest symmetric mode may be mixed in with the analyzed region of the waveform.

Fig. 5 shows the measured velocity for the lowest antisymmetric mode versus temperature at two frequencies. The velocity decreases with temperature; slopes for both cases are 0.324 m/s°C. Fig. 6 shows relative velocity changes where \( v_0 \) is the velocity at the ambient temperature. It is obvious that while the variation in velocity with temperature is small, it can still be detected by the employed digital signal processing method. The relative velocity changes based on experimental data are 0.24\( \times 10^{-3} \)/°C at 0.5 MHz and 0.17\( \times 10^{-3} \)/°C at 1.0 MHz. The data variation (difference between the measured velocity and the linear regression result) is lower at the higher frequency (about 0.723 m/s for 1 MHz and 1.266 m/s for 0.5 MHz). This indicates that a more precise velocity (and thus temperature) determination can be achieved at higher frequencies than at lower ones. Based on the results shown in Fig. 5, it is estimated that a 5°C precision in temperature measurement can be achieved at 0.5 MHz, while a 3°C precision can be
Fig. 5  Measured phase velocities versus temperature at two frequencies.

Fig. 6  The relative velocity changes versus temperature.
achieved at 1 MHz. Utilizing all the frequency components will give a better precision.

The work reported above has demonstrated the possibility of using ultrasonic velocity measurements to determine the temperature of any semiconductor substrate whose elastic constants vary with temperature (all do). The temperature resolution depends upon the precision of the velocity measurements and frequency. Using recently developed digital signal processing methods, we have demonstrated that 3°C or better precision in temperature measurement is readily achievable.

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