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Characterization of Young's modulus of silicon versus temperature using a "beam deflection" method with a four-point bending fixture

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Abstract

Young's modulus (E) and Poisson's ratio (v) are dependent upon the direction on the silicon surface. In this work, E and v of silicon have been calculated analytically for any crystallographic direction of silicon by using compliance coefficients (s_{11}, s_{12}, and s_{44}), and the values of E are confirmed experimentally by using a "beam deflection" method with a four-point bending fixture. Experimental results for E as a function of temperature from −150 °C to +150 °C are presented for (0 0 1) and (1 1 1) silicon wafers.

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Keywords: Young's modulus (elastic modulus); Poisson's ratio; 4PB; Beam deflection

1. Introduction

Our research group is heavily involved in understanding and modeling reliability of packaged integrated circuits over a very broad temperature range (77–500 K). Silicon is the dominant material in semiconductor device fabrication and temperature dependent material properties of crystalline silicon, E (Young's modulus) and ν (Poisson's ratio), are important for proper modeling of stress and strain in electronic packaging [1]. Also, the structures of MEMS (micro-electro-mechanical systems) devices, one of the most exciting areas of microelectronic activity, are based on the fabrication of mechanical devices in silicon [2], and accurate knowledge of mechanical properties of silicon is required for design of MEMS devices.

Silicon is an anisotropic material and it is often overlooked that Young's modulus E and Poisson's ratio v are dependent on direction. This work presents theoretical and experimental results for the E and v from −150 °C to +150 °C for the (0 0 1) and (1 1 1) surfaces important in modern microelectronic fabrication.

Wortman et al. [3] analytically calculated Young's moduli for an arbitrary rectangular coordinate system as a function of direction cosines in the silicon crystal. In addition, they plotted the graphs of these moduli as a function of crystal direction for orientations in the (1 0 0) and (1 1 0) planes.

Kang [4] used a strain gage technique to measure E of silicon with a four-point bending fixture in which the gages are mounted on the surface of specimen strips. Micro-testers have also been used to measure E. However, this method has some limitations for measuring E of stiff materials such as silicon. In this work, a "beam deflection" technique [5] with a four-point bending (4PB) fixture is utilized to determine E experimentally for (0 0 1) and (1 1 1) silicon. The results are compared to graphs of E for important directions on the (0 0 1) and (1 1 1) silicon wafer planes

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versus temperature are plotted. The experimental values of E at room temperature are observed to be in agreement with analytic calculations based upon literature values of the stiffness coefficients [3].

2. Contemporary crystal planes

Silicon has a crystal lattice of "faced-centered cubic diamond structure" and the arrangement of silicon atoms in its lattice is depicted in Fig. 1a. The surface of silicon (e.g. (0 0 1) or (1 1 1)) refers to a specific set of atomic planes in that structure, and those planes are also presented in Fig. 1a for better understanding the crystal geometry of silicon. We are interested in (0 0 1) and (1 1 1) oriented silicon wafers whose geometries are given in Fig. 1b and c, respectively. In the current microelectronics industry, the vast majority of silicon devices are now fabricated using (0 0 1) silicon wafers. On the other hand, (1 1 1) wafers are still used for traditional bipolar fabrication as well as in piezoresistive stress sensors [2].

The surface of an (0 0 1) oriented silicon wafer is a (0 0 1) plane, and the [1 0 0] direction is normal to the plane. The axes of the natural wafer coordinate system $x_1' = [110]$ and $x_2' = [\bar{1}10]$ lie parallel and perpendicular to the primary wafer flat. The primed axes x_1' and x_2' are aligned with the normal orientation of a chip on the wafer, whereas the unprimed axes x_1 and x_2 represent the principal crystallographic axes. The surface of (1 1 1) oriented silicon wafer is a (1 1 1) plane, and the [1 1 1] direction is normal to the wafer plane. The crystallographic axes $x_1 = [100]$, $x_2 = [010]$, and $x_3 = [001]$ no longer lie in the wafer plane. The x_1' and x_2' coordinates are chosen perpendicular and parallel to the wafer flat.

Silicon exhibits linear elastic material behavior, and Hooke's law, describes the linear elastic stress–strain relation:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{1}$$

where σ_{ij} and ε_{kl} are the stress and strain components, and C_{ijkl} are the components of the stiffness tensor. Inverting Eq. (1) gives

$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl} \tag{2}$$

where S_{ijkl} are the compliance components. Also, the transformation relations for the reduced index stress and strain components can be expressed as indicated below [4]:

$$\sigma_\alpha = T^{-1}_{\alpha\beta}\sigma'_\beta \tag{3}$$

$$\varepsilon_\alpha = T^{t}_{\alpha\beta}\varepsilon'_\beta \tag{4}$$

where the coefficients $T_{\alpha\beta}$ are elements of a six-by-six transformation matrix related to the direction cosines between an arbitrary coordinate system and the crystallographic coordinate system for the silicon wafer.

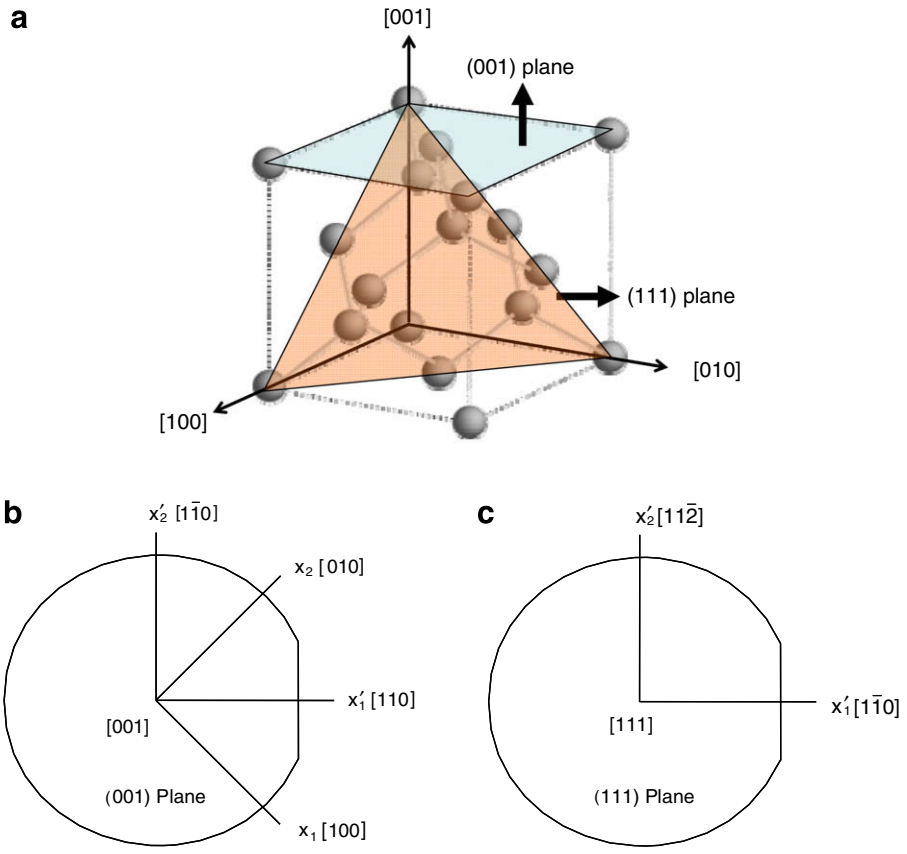

Fig. 1. (a) The basic diagram of silicon crystal structure, (b) general (0 0 1) silicon wafer geometry and (c) general (1 1 1) silicon wafer geometry.