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Thermal characterization of epitaxial grown polycrystalline silicon

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ABSTRACT

The thermal conductivity of various epitaxial grown polycrystalline silicon layers was measured by using the 3-ω-method. Heater widths of 20 μm, 55 μm and 80 μm were structured applying standard photolithography. Experimental values are given, depending on layer thickness, ranging from 5 μm to 50 μm, the impurity concentration, the deposition temperature and recrystallization time. The measured values were used to discuss the cross-plane and in-plane thermal conductivity.

1. Introduction

The thermal improvement of electronic systems, especially of integrated circuits (ICs) and micro-electro-mechanical systems (MEMS) is based on the characterization of the physical properties of each material and layer in the system. Extensive research is done on thermal conductivity of monocrystalline and thin polycrystalline silicon with thickness smaller than 1 μm, but less on thermal conductivity of thick epitaxial grown polycrystalline silicon with thickness bigger than 1 μm which is used for inertial sensor applications for example [1, 2]. While LPCVD (low pressure chemical vapor deposition) or sputtering processes are used for thin polycrystalline silicon layers up to a few micrometers, epitaxy is used for thick layers since a high deposition rate of 4 to 5 μm/min is achieved. Therefore epitaxial grown polycrystalline silicon is required in ICs and MEMS technology. A big difference between thick and thin epitaxial grown polycrystalline silicon is the grain size of such films. Due to the fact that the grain size increases with polycrystalline silicon layer thickness an improvement of the thermal conductivity at thicker layers is expected. In contrast to polycrystalline silicon, monocrystalline silicon is not supposed to show such an effect. Additional effects such as the impurity concentration, the temperature and recrystallization time that may influence the thermal conductivity has been examined.

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2. Theory

The thermal conductivity can be measured with steady state or transient methods. Using steady state methods a constant heat flow is applied to the sample and a temperature drop is measured. Cahill developed a transient measurement method for the thermal conductivity. The method is called 3-ω-method [3]. This method enables the measurement of the thermal conductivity in a wide temperature range up to 1000 K. The failure is less than ±2% at all temperatures. On a temperature-dependent resistor a sinusoidal electrical current with the frequency ω is applied. This current generates a 2-ω oscillation, the resistance and the temperature amplitude. The voltage has a ω and a 3-ω part. The oscillation parts cause the thermal diffusion wave into the sample. It varies with geometry and thermal diffusivity. To calculate the thermal conductivity, the real- and imaginary-part of the 3-ω voltage are plotted over the logarithmic frequency. From the real part a slope and from the imaginary part a straight line can be calculated. The thermal conductivity can be calculated from the slope of the real part. Eq. (1) describes the temperature oscillation ΔT of the heater line.

$$\Delta T = \frac{P}{l\pi\lambda}(-\ln(qb) + const.) = \frac{P}{l\pi\lambda}\left(-\frac{1}{2}\ln(\omega) - \frac{1}{2}\ln\left(\frac{ib^2}{a}\right) + const.\right) \quad (1)$$

with P/l: heater power per unit length (W/m), λ: thermal conductivity (W/(mK)), 1/q: thermal penetration depth (m), b: heater

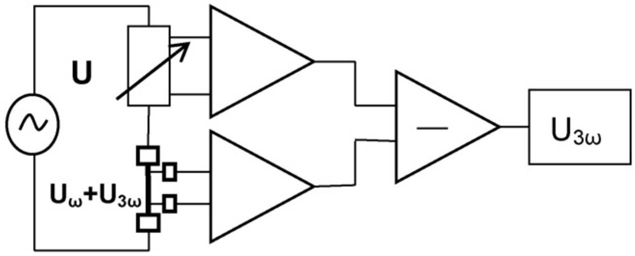

Fig. 1. Electrical circuit diagram.

half width (m), a: thermal diffusivity (m^2/s), ω: angular modulation frequency (1/s).

After rearranging the real part the thermal conductivity is:

$$\lambda = \frac{U^3 ln\left(\frac{f2}{f1}\right)}{4l\pi R^2 (U_{3\omega,1} - U_{3\omega,2})} \frac{dR}{dT} \quad (2)$$

with R: resistance (Ω), $\frac{1}{R}\frac{dR}{dT}$: temperature coefficient (1/K), f: frequency (1/s), U: voltage (V), $U_{3\omega}$: real part of 3 ω voltage (V), l: length of the line (m).

In case of anisotropy the slope method can be used to measure the cross-plane thermal conductivity (one-dimensional heat flow), if the heater width is larger than the thickness of the measured thin layer. To measure the in-plane thermal conductivity, the width of the heater must be smaller or comparable to the thickness of the measured layer. In this case the heater is more sensitive to a two-dimensional heat flow. Hence using a two-dimensional equation it is possible to calculate the in-plane thermal conductivity [4].

$$T = \frac{P}{\pi l \lambda_{sz}\sqrt{\frac{\lambda_{xy}}{\lambda_z}}}\left(0,5\, ln\left(\frac{a_{sz}\frac{\lambda_{xy}}{\lambda_z}}{b^2}\right) - 0,5\, ln\,(\omega) + \eta\right) - i\left(\frac{P}{4l\lambda_{sz}\sqrt{\frac{\lambda_{xy}}{\lambda_z}}}\right) \quad (3)$$

with b: heater half width (m), a_{sz}: cross-plane thermal diffusivity of substrate (m^2/s), λ_{sz}: cross-plane thermal conductivity of substrate (W/(mK)), λ_{xy}: in-plane thermal conductivity (W/(mK)), λ_z: cross-plane thermal conductivity (W/(mK)), η: constant (−).

The major measurement parameters were $P/l = 8$ W/m with a resistance of 80 Ω in case of the narrow heater width and 20 Ω in case of the wider heater width.

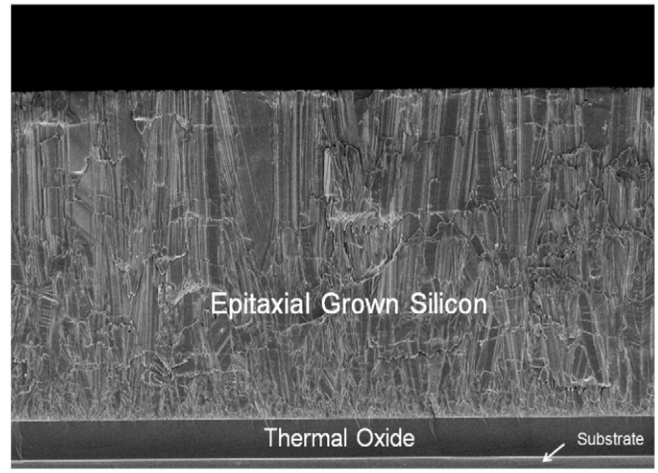

Fig. 3. Cross view of a sample consisting of a substrate, a 2.5 μm thermal oxide and an epipoly silicon film.

3. Experimental

3.1. Measurement setup

The measuring setup is a self-construction and consists of a current source (Keithley 6221 AC mode), a high precision decade resistance, a vacuum chamber, a Lock-Inn amplifier and the electrical circuit. The frequency can be varied between 0.1 Hz and 105 kHz with a maximum amplitude of 105 mA. Therefore a heater structure designed in four-wire technique to minimize edge effects (Fig. 4) was used. The response signal was analyzed with LabVIEW using Fast Fourier Transformation. In order to compensate the first order oscillations a high precision decade resistance is adjusted. Furthermore, the electrical circuit with the operational amplifiers allows determining the 3-ω signal (Fig. 1). Then the real- and imaginary-part can be analyzed by using a Lock-In amplifier.

Fig. 2a shows the complete measurement setup. There are challenges such as the minimization of thermal losses by convection and the electrical contacting of the samples. In order to minimize the thermal losses the measurement is done in a vacuum chamber with a pressure of about 10^{-4} mbar. For the purpose of contacting and avoiding damage on the contact pads half-rounded gold coated spring contact pins were used (Fig. 2b).

3.2. Sample preparation

The samples discussed in this paper are epitaxial films grown from gaseous precursors instead of monocrystalline bulk silicon. This kind of silicon has a lower thermal conductivity than monocrystalline silicon

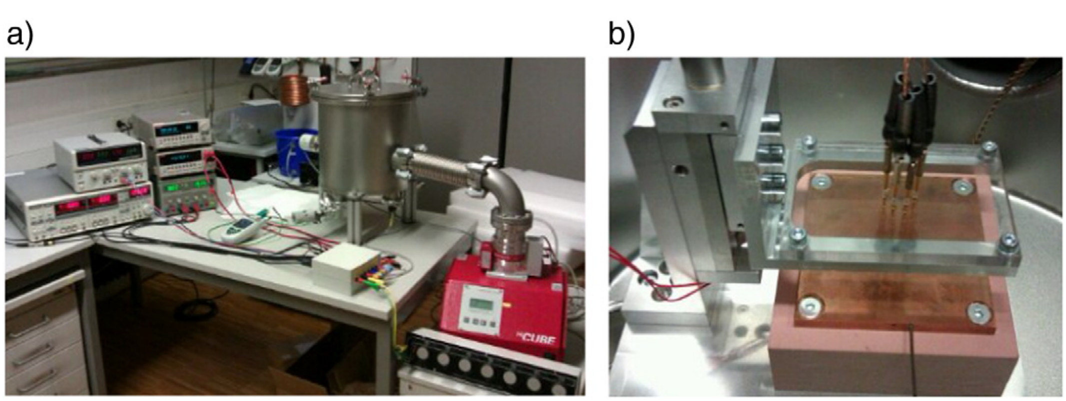

Fig. 2. a): Measurement setup for 3-ω measurement: Vacuum chamber (center) and vacuum pump (right) b): Contacting system with spring contact pins.