IN-PLANE THERMOELECTRIC PROPERTIES CHARACTERIZATION OF A Si/Ge SUPERLATTICE USING A MICROFABRICATED TEST STRUCTURE

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ABSTRACT

In this work we present an experimental technique for the characterization of thermoelectric properties of thin films in the in-plane direction. The technique employs a micro-fabricated array of heaters/sensors deposited onto the film in order to monitor the temperature, the Seebeck voltage and the electrical voltage of the thermoelectric film. The thermal diffusivity and thermal conductivity of the film are determined from the decay of the temperature profile detected over a wide frequency range by arrays of temperature sensors around a microscale heater. The temperature profile and the Seebeck voltage monitored by the voltage electrodes are used to determine the Seebeck coefficient of the thermoelectric films in the in-plane direction. The substrate influence on the thermoelectric properties measurements is eliminated by the removal of the substrate over a wide area underneath the heater and the monitoring electrodes. Electrical conductivity measurements are carried out without heating based on the 4-probe method. Test structures are fabricated and thermoelectric properties characterization is carried out for a Si/Ge superlattice.

INTRODUCTION

The predicted enhancement in the efficiency of thermoelectric energy conversion devices based on quantum effects in low-dimensional structures [1] draws a strong interest for the characterization of the thermal conductivity, Seebeck coefficient, and electrical conductivity of various multilayer thin film systems [2-6]. However, thermoelectric properties characterization of thin-films is a challenging task. For example, due to the anisotropic properties of the multilayer structures, thermoelectric characterization must be carried out for both the in-plane (parallel to the film plane) and the cross-plane directions. Moreover, the thermoelectric films are often deposited on semiconductor substrates and/or buffer layers, which could affect the measurement accuracy due to their high Seebeck coefficient, large electrical conductance, and dominant contribution to heat transport in the in-plane direction. Furthermore, it is necessary to develop techniques capable of measuring all properties on the same sample. Currently, characterization of thin films thermoelectric properties along the in-plane direction is typically carried out using separate experimental setups and different samples for each thermoelectric property measurement [7]. Characterizing all thermoelectric properties on the same sample was reported only for films deposited on thin, electrically insulating substrates and with low thermal conductivity [8].

This paper presents experimental measurements of the thermoelectric properties of a Si/Ge superlattice in the in-plane direction based on a novel experimental method capable of measuring all the in-plane thermoelectric properties of thin films on the same sample. The technique employs a micro-fabricated array of heaters/sensors deposited onto the film in order to monitor the temperature, the Seebeck voltage and the electrical voltage of the thermoelectric film. The substrate influence on the film thermoelectric properties measurements is reduced by the removal of the substrate over a wide area underneath the heater and the monitoring electrodes. The thermal conductivity of the film is measured from the decay of the ac temperature profile detected by arrays of temperature sensors around a microscale heater subjected to modulated joule heating. The temperature profile and the Seebeck voltage monitored by the voltage electrodes are used to determine the
Seebeck coefficient of the thermoelectric films in the in-plane direction. Electrical conductivity measurements are carried out without heating based on the 4-point-probe method.

**NOMENCLATURE**

C  quantity defined in Eq. (2), K

e  exponential function

F  correction factor

I  electrical current, A

k  thermal conductivity, Wm⁻¹K⁻¹

L  length of the heater, m

m  complex quantity defined in Eq. (3), m⁻¹

q  heat flux amplitude, Wm⁻²

T  temperature amplitude, K

V  voltage, V

W  half width of the membrane, m

w  film thickness, m

α  thermal diffusivity, m²s⁻¹

β  temperature coefficient of resistance, K⁻¹

γ  quantity defined in Eq. (3), m⁻¹

δ  complex quantity defined in Eq. (3), m⁻¹

σ  electrical conductivity, Ω⁻¹m⁻¹

θ  complex temperature amplitude, K

ω  angular modulation frequency, rad s⁻¹

**Subscripts**

2ω  corresponding to 2 times the angular modulation frequency

DC  corresponding to the DC component

g  geometrical

sp  related to probe spacing

//  in-plane direction

**PRINCIPLE AND SAMPLE FABRICATION**

Figure 1 (a) and Fig 1 (b) shows respectively a top and a cross-sectional view of the test structure indicating the array configuration and the function of the electrodes. The thermal conductivity of the film is measured from the decay of the temperature profile detected by arrays of temperature sensors around a microscale heater. The temperature measurement is based on the thermoresistive effect in the metal lines, i.e. the resistance change of the metal line is directly proportional to the temperature change. The heater and temperature sensor electrodes (typically 5μm wide) are insulated from the electrically conductive surface of the thermoelectric film by a dielectric thin film deposited onto the thermoelectric film during the microfabrication process of the testing structure. The substrate influence on thermoelectric properties measurements is reduced by the removal of the substrate over a wide area (1mm×1mm) underneath the heater and the monitoring electrodes. The temperature profile and the Seebeck voltage monitored by the voltage electrodes are used to determine the Seebeck coefficient of the thermoelectric film in the in-plane direction. The dielectric film is removed over a small area (5μm×10μm) underneath the middle section of the voltage electrodes in order to allow direct contact to the thermoelectric film and to permit the measurement of the Seebeck voltage. Electrical conductivity measurements are carried out without heating based on the 4-point-probe method, albeit by replacing the pin-contact in a normal four point probe by microfabricated contact points and lines. Electrical current is injected through the outer voltage electrodes and the voltage drop in the thermoelectric film is detected by the inner voltage electrodes.

The studied SiGe superlattice was grown by the Molecular Beam Epitaxy technique [9] on silicon-on-insulator (SOI) substrate. The sample configuration before the microfabrication of the thermoelectric testing structure is shown in Fig. 2. The SOI substrate is a two-layer film sandwich of 3800Å SiO₂ film and 1800Å of Si film on top of the Si substrate. The Si film serves as a starting layer for the epitaxial growth of the graded buffer layer with a total thickness of 1.3μm. The buffer layer is required in order to compensate the lattice mismatch between the lattice constant of the Si substrate and the lattice constant of
the superlattice film. The superlattice film is a periodic Si(20Å)/Ge(20Å) multilayer structure with a total thickness of 0.4µm.

The fabrication of the heater/sensor array and the removal of the substrate are performed using typical micro-fabrication techniques. A layer of SiN (3000Å) was deposited by plasma enhanced chemical vapor deposition (PECVD) in order to serve as electrical insulation between the metallic array of sensors and the superlattice film. Via-holes patterned in the nitride layer by plasma etching allow direct contact to the Si/Ge superlattice film and enable the measurement of the Seebeck voltage by the voltage probes. Furthermore, 300Å of Sb and 1200Å of Au deposited into the via-holes by electron beam deposition serve as a local dopant source and promote good electrical contact between the voltage probes and the superlattice film. Electron beam deposition of Au (3000Å) is used to fabricate the array of heaters/sensors. The substrate material underneath the sensors is removed by deep reactive-ion-etching (DRIE) based on the Bosch process [10]. The SiO2 layer adjacent to the Si substrate is used as a high selectivity (>150:1 for Si and thermal SiO2) etch stop and it is estimated that less than 30% of the SiO2 film thickness is removed during the final 5min step of the etching process. The front surface of the sample is protected during the DRIE etch by a 1µm thick PR which is later used to provide mechanical stability to the etched membrane during handling and the experimental procedure. The studied Si/Ge sample is instrumented with an array of heaters, temperature sensors and voltage probes, equally distanced at 80µm from each other. The size of the free-standing film structure on which thermoelectric characterization is performed is approximately 1mm x 1mm and is composed of a sandwich of 6 layers with a total thickness of ~3.56µm (0.38µm SiO2, 0.18µm Si, 1.3µm buffer, 0.4µm Si/Ge superlattice, 0.3µm SiN and 1µm photoresist).

**Heat Conduction Modeling**

One of the methods developed for the in-plane thermophysical properties characterization of free-standing thin films is the ac calorimetry [11]. In this technique, a thermal wave is created into the film by modulated heating, and the temperature response is monitored as a function of the distance to the heated region of the sample. The heating source is typically generated by the absorption into the film of light or laser radiation with different beam configurations [11-13] or by Joule heating into a microfabricated electrical heater [7, 14]. The temperature measurement is performed by a fine thermocouple [11-13], a photolithographically patterned temperature sensor [7, 14-15], or by non-contact infrared detection [16]. The sample boundary effects are usually neglected and one-dimensional heat conduction modeling is used to extract the thermal diffusivity of the film. Hatta et al. [17] presented a one-dimensional model for the sample size effects on the measured sample diffusivity. Chen and Yu [18] established a two-dimensional model for the finite sample effect and used numerical simulation to calculate the equivalent thermal diffusivity as a function of the modulation frequency.

Analytical solutions of one-dimensional and two-dimensional heat conduction models are employed in this work to predict the ac temperature profile in the free-standing film under modulated heating. Figure 3 shows schematically the models configurations. An ac-modulated current with angular frequency $\omega$ passes through the heater and generates a dc and an ac heating component modulated at $2\omega$. Therefore, the solution for the temperature rise in the membrane is the superposition between a dc temperature component and an ac temperature modulated at $2\omega$ angular frequency. The models’ assumptions
for the ac heating are: membrane symmetry with respect to the heater, no temperature gradients across the membrane thickness, no convection and radiation losses, neglecting heat conduction through the metallic wires of the heater and sensor array, and zero temperature amplitude at the edges of the membrane.

Using the method of separation of variables the solution for the two-dimensional complex temperature amplitude $\theta$ is then of the form:

$$\theta(x, y) = \sum_{n=1}^{\infty} C_n \left( e^{i\gamma_n x} + e^{-i\gamma_n x} \right) e^{i\delta_n y} + e^{-i\delta_n y}$$

where,

$$C_n = \frac{q}{k_{//}} \frac{2(-1)^{n+1} + 1}{\pi \sqrt{\gamma_n^2 - m^2}}$$

$$\gamma_n = \frac{n\pi}{L}, \quad \delta_n = \pm \sqrt{\gamma_n^2 - m^2}, \quad m^2 = \frac{i2\omega}{\alpha_{//}}$$

L is the heater length, W is half width of the membrane, $q$ is half the amplitude of the total heat flux generated by the heater at $y=W$, and $\alpha_{//}$ and $k_{//}$ are respectively the in-plane thermal diffusivity and thermal conductivity of the film. Equation (1) contains both the amplitude and the phase of the ac temperature and can be used to determine the thermophysical properties of the film by fitting the experimental temperature signals collected at different locations and modulation frequencies.

A simpler one dimensional heat conduction model could be possibly employed for faster data processing of the experimental results. Assuming the heater of infinite length ($L \to \infty$), the solution for the complex temperature rise in the membrane becomes,

$$\theta(y) = \frac{q}{k_{//} m^2} \left[ e^{my} - e^{m(2W-y)} \right]$$

The thermal diffusivity of the membrane can be then determined based on an established ac calorimetric method, [11]. For $W \to \infty$, if the thermal signal is collected at the same frequency for different locations away from the heater, the thermal diffusivity of the membrane can be inferred from the slope of the phase and/or the slope of the logarithm of amplitude plotted as a function of location $y$ [13]:

$$\alpha_{//} = \frac{\omega}{\text{slope}^2}$$

Furthermore, the thermal effusivity of the film could be determined if the heater temperature amplitude for different modulation frequencies is plotted as a function of $1/\sqrt{2\omega}$. The curve has a linear region and the slope yields the inverse thermal effusivity of the membrane,

$$\sqrt{\frac{\alpha_{//}}{k_{//}}} = \frac{\text{slope}}{q}$$

The film thermal conductivity can be extracted using the previously determined values of the film diffusivity.

**EXPERIMENTAL RESULTS AND DISCUSSION**

Due to the complexity of the currently studied film (a 6-layer structure), the free-standing membrane is treated as an effective media with the total thickness of 3.56µm. The relative film thickness uncertainty due to the unknown thickness of the SiO$_2$ layer after the DRIE etch step is estimated to be < 3%.

**Thermophysical Properties Measurement**

Modulated electrical current with frequencies between 1Hz and 1000Hz is passed through a heater symmetrically positioned with respect to the edge of the membrane. In this frequency range, temperature drop across the total film thickness is very small so that heat conduction is in the film plane only. The temperature signal is monitored for the heater and several temperature sensors situated at various distances away from the heating source. The modulated heating generates a voltage oscillation across the heater at three times the modulation frequency of the electrical current. This 3$\omega$ voltage can be used to infer the temperature amplitude of the heater [19]. In order to measure the temperature rise of the temperature sensors, a small dc current from a battery or a very stable power supply is passed through the sensors. The dc current multiplied with the 2$\omega$ temperature induced oscillations in resistance gives rise to a 2$\omega$ voltage proportional to the temperature amplitude of the sensor. Therefore the temperature amplitude of the sensor is,

$$T_{2\omega}^{\text{sensor}} = \frac{V_{2\omega}}{V_{\text{DC}}}$$

where $V_{2\omega}$ is the voltage amplitude detected at 2$\omega$ angular frequency across the sensor, $V_{\text{DC}}$ is the dc voltage drop across the same section of the sensor and $\beta$ is the temperature coefficient of resistance for the sensor.

Figure 4 shows the averaged experimental temperature amplitude collected across the 500µm middle section of the heater and plotted as a function of $1/\sqrt{2\omega}$. The curve has a linear region for current frequencies between ~ 40Hz and 1000 Hz. A fit to the linear region is shown with solid line in Fig. 4. The linear behavior of the signal suggests the applicability of...
the one-dimensional heat-conduction model. This is because at high modulation frequencies the heat-affected region is confined close to the heater and the heater edge effects and two-dimensional effects into the film are minimized. However, the thermal diffusion length should be larger than the film thickness in order to avoid temperature gradients in the cross-plane direction of the film. These conditions being met, the film effusivity could be determined based on the slope of the linear region and Eq. (6). The measured effective inverse thermal effusivity value for the membrane is \(1.335 \times 10^{-4} \text{m}^2\text{KW}^{-1}\text{s}^{-0.5}\).

Figure 5 shows the averaged experimental temperature amplitude collected across the heater and two temperature sensors situated at respectively 160µm and 320µm distance from the heater. In order to determine the thermal conductivity and thermal diffusivity of the membrane, the experimental temperature signal collected between 10Hz and 100Hz is compared to the predictions of the two-dimensional heat conduction model (Eq. 1). The fitting was carried out using the measured value of the effective thermal effusivity and varying the thermal conductivity of the membrane. The best fit is shown with solid lines in Fig. 5 and was obtain for an effective thermal conductivity of 14.5W/mK and an effective thermal diffusivity of \(3.74 \times 10^{-6}\text{m}^2/\text{s}\). The predicted temperature rise is above the experimental values. The deviation from the model predictions is larger for the one-dimensional model, which did not considered the edge effects associated with the finite size of the membrane in the direction of heater length. Furthermore, both heat conduction models did not considered the natural convection losses from the surface of the membrane and conduction losses through the gold wires forming the sensor/heater array. These heat losses contribute to the reduction of the membrane temperature mainly at low modulation frequencies and may explain the discrepancies between the predictions of the two-dimensional model and the experimental results. Electrodes with smaller thickness would reduce the conduction losses and possibly improve the thermal conductivity measurement accuracy.

If the assumption of one-dimensional heat conduction is valid, then Eq. (5) could be used to determine the thermal diffusivity of the film using the phase and the logarithm of the amplitude signal collected at various distances away from the heater. The calculated thermal diffusivity of the film from both amplitude and phase signals is shown in Fig. 6 as a function of modulation frequency. At low frequencies, the one-dimensional approximation is not valid and the model yields frequency dependent values for the thermal diffusivity. For frequencies larger than 40Hz, the calculated thermal diffusivity becomes frequency independent, indicating the applicability of the one-dimensional model. For this frequency range, the thermal diffusivity of the film is between \(4.9 \times 10^{-6}\text{m}^2/\text{s}\) (from phase) and \(3.8 \times 10^{-6}\text{m}^2/\text{s}\) (from amplitude). As expected, the thermal

![Fig. 4](image1.png)

Fig. 4 The averaged experimental heater temperature amplitude as a function of \(\sqrt{2\omega}\).

![Fig. 5](image2.png)

Fig. 5 The averaged experimental temperature amplitude of the heater and two temperature sensors situated at respectively 160µm and 320µm distance, as compared with the predictions of two-dimensional (solid line) and one-dimensional (dashed line) heat conduction models for an effective thermal conductivity of 14.5W/mK and an effective thermal diffusivity of \(3.74 \times 10^{-6}\text{m}^2/\text{s}\).
diffusivity value inferred from the amplitude signal is consistent with the value reported in Fig. 5. However, the thermal diffusivity inferred from the phase signal is about 30% higher. Therefore, using the effusivity from Fig 4 it yields a thermal conductivity of 16.6W/mK, about 14% larger than the 14.5W/mK thermal conductivity calculated based on the amplitude signal. This discrepancy in the measured thermal conductivity value is larger than the ~3% thermal conductivity error due to uncertainty in the total thickness of the membrane structure.

**Measurement of the Seebeck coefficient**

Seebeck voltages are collected during the modulated heating of the membrane by monitoring the voltage drop between a reference electrode and voltage probes situated at different distances from the heater. It is important for the measurement accuracy to keep a constant temperature of the reference electrode. In order to minimize possible temperature oscillations of the reference due to the modulated heating, the reference probe contacts the thermoelectric film in an area away from the free-standing membrane (see Fig. 1 (a)). Furthermore, the accuracy of the Seebeck measurement is increased if the voltage probe monitoring the Seebeck voltage is situated closer to the heating source. This is because the larger is the temperature difference between the monitoring probe and the reference electrode the less important are the uncertainties induced by the possible temperature oscillations of the reference. Figure 7 shows the amplitude of the Seebeck voltage as a function of modulation frequency, measured between the reference electrode and a voltage probe situated at 80µm distance from the heating source.

The temperature amplitude of the Seebeck probe must be interpolated in order to calculate the Seebeck coefficient of the thermoelectric film. A simple way to perform the interpolation is to plot the logarithm of the temperature amplitude as a function of sensor position. As shown by the examples in Fig. 8, the profile is linear and the calculation of the Seebeck probe temperature is straightforward. Since the measured sensor temperature is actually an averaged temperature over the 500µm middle section of the sensors, the interpolated temperature would correspond to a similar averaging length of the voltage probe. However, the voltage probe averaging length is only 10µm and its temperature would be closer to the maximum temperature rather than to the average temperature in the middle section. In order to correct for this discrepancy, the two-dimensional heat conduction model was used to find the relationship between the maximum and the average temperature over the 500µm middle section, at each modulation frequency and for given sensor position and thermophysical properties of the membrane. The correction factor for the maximum temperature rise in the voltage probe varies from ~1.07 at 1Hz modulation frequency to ~1.02 at 20Hz, further decreasing to 1 at higher frequencies. With these correction factors, the Seebeck coefficient is -311.5 µV/K at 1Hz, -331.4 µV/K at 20Hz and -344.4 µV/K at 40Hz. The 10% variation over the frequency range is attributed to uncertainties in the reference temperature. This effect becomes more important as the temperature difference between the monitoring probe and the reference electrode decreases at higher frequencies. As with the thermal conductivity values reported in the previous section, the values of the Seebeck coefficient reported here apply for the effective membrane structure. The sign of the Seebeck coefficient was
Fig. 8 An interpolation technique based on the temperature rise of the heater and two temperature sensors is used to determine the temperature rise of the Seebeck electrode.

determined during dc testing of the membrane. DC current was passed through the heater and the polarity of the Seebeck voltage drop at the Seebeck electrodes was determined. The negative sign, indicates n-type conduction, and is consistent with the doping type for the studied superlattice.

**Electrical conductivity measurement**

A direct approach to measuring the electrical conductivity of semiconductor materials is to pass a current through the sample and to measure the voltage drop across a known distance. A well-established technique is the four-point-probe. Several correction factors are applied, as necessary, to obtain accurate measurements of the electrical conductivity [20]. The corrections factors applicable to this experiment consider the non-uniform spacing between the probes (F_{SP}), the ratio between the film thickness and the probe spacing (F(w/s)) , and the geometrical size of the sample (F_g).

The electrical conductivity \( \sigma \) of the specimen can be calculated from,

\[
\frac{I}{\sigma w} = \frac{V}{I} \cdot F_{SP} \cdot F \left( \frac{w}{s} \right) \cdot F_g
\]

The electrical conductivity measurements are carried out without heating in the membrane. Figures 9 (a) and 9(b) shows two examples of the experimental I/V curves measured using the 4-point-probe technique in two different configurations. The first configuration, shown in the inset of Fig. 9(a), is similar to a typical 4-point probe measurement. The probes are collinear, equally spaced at 320\( \mu m \) from each other, and each probe contacts the film over a small area of 10\( \mu m \times 5\mu m \). One difference to a typical 4-point measurement is the presence of two passive (not connected to outside circuits during this experiment) and large size electrodes situated in between the current and voltage probes. Assuming that these electrodes have no effect on the electrical conductivity measurements, than the electrical conductivity of the film can be inferred from the slope of the I/V curve and Equation (8). The probe spacing correction factor and the thickness correction factors are unity. The geometrical correction factor is calculated based on the ratio between the width of the sample (~5.4mm) and the probe spacing. The geometrical correction factor is ~4.38, which is about 4% smaller than the geometrical correction factor for an infinite size sample [20]. Therefore, the measured value of the effective electrical conductivity of the structure is (assuming 3.56\( \mu m \) membrane thickness) \( \sigma=0.54\times10^4 \Omega^{-1} m^{-1} \). However, the structure contains several electrical insulating layers (photoresist, silicon dioxide, silicon nitride) or highly resistive
layers (buffer and silicon) and the true electrical conductivity of the superlattice is probably much higher than the effective electrical conductivity reported above. For example, assuming that the superlattice layer has the major contribution to electrical conductivity, the superlattice conductivity becomes, $\sigma = 4.81 \times 10^4 \Omega^{-1} \text{m}^{-1}$.

The second configuration for the 4-probe electrical conductivity measurement is shown in the inset of Fig. 9(b). In this configuration there are no passive electrodes situated between the current and voltage probes. However the probe spacing is not equal and the contact area to the film is 900$\mu$m$\times$5$\mu$m for the current probes and 10$\mu$m$\times$5$\mu$m for the voltage probes. Since Eq. (8) does not apply for this configuration, numerical modeling is carried out to find the relation between the electrical conductivity of the film, the current $I$ injected through the large outer electrodes, and the measured voltage drop $V$. The simulation considers the actual size of the sample. The relation between the electrical conductivity $\sigma$, the current $I$, and the voltage drop $V$ is inferred as,

$$\frac{1}{\sigma w} = \frac{V}{I} \cdot \frac{1}{0.218} \quad (9)$$

Therefore, the measured effective electrical conductivity of the membrane in this experimental configuration is $\sigma = 0.63 \times 10^4 \Omega^{-1} \text{m}^{-1}$ (or $\sigma = 5.67 \times 10^4 \Omega^{-1} \text{m}^{-1}$ for the superlattice itself assuming that superlattice layer is the major contributor to the electrical conductivity). The electrical conductivity measured in the last electrode configuration is about 18% larger than the electrical conductivity value reported earlier for the typical four-point probe configuration. The discrepancy is probably caused by the unaccounted influence, in the first experimental setup, of the large passive electrodes on the electric field.

**SUMMARY AND CONCLUSIONS**

This work demonstrates simultaneous characterization of all the thermoelectric properties in the in-plane direction of thin-films. The method employs an array of micro-fabricated heaters/temperature sensors and voltage probes deposited on a free-standing thermoelectric membrane. Substrate removal eliminates unwanted contributions from the substrate to the thermal and electrical signals collected from the sample. The array is used to monitor the Seebeck voltage, electrical voltage and temperature profile at various modulation frequencies. Theoretical models are developed in order to back-up the thermoelectric properties of the film from the experimental signals. Experimental measurements are carried out for a 20Å/20Å Si/Ge superlattice film grown on a silicon on insulator substrate. Due to the complexity of the six-layered-film sample, only effective thermoelectric values applicable to the entire structure are reported. An electrical conductivity of $\sim 0.63 \times 10^4 \Omega^{-1} \text{m}^{-1}$, Seebeck coefficient of approximately 311.5 $\mu$V/K and thermal conductivity of $\sim 15.5 \text{W/mK}$ are reported for the studied membrane structure. In order to back-up the superlattice properties, the contribution of the additional layers must be evaluated. One possible way to estimate this contribution is to perform additional measurements on a similar structure without the superlattice film or to reduce the numbers of layers by selective etching during the sensor array fabrication process.

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**REFERENCES**


