Determining the thin-film thermal conductivity of low temperature PECVD silicon nitride

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Abstract: The design and optimization of micromachined thermal sensors often requires information on accurate material properties of the used thin-films. These data can differ considerably from those stated for bulk matter and are strongly process-dependent. In this contribution a micromachined canitlever structure is proposed, which allows to directly determine the thermal conductivity of dielectric thin-films from a single steady-state measurement without the need of a complex mathematical model. For low temperature PECVD nitride a thermal conductivity of 1.18 W/m^{-1}K^{-1} was obtained, which is below the literature values reported for standard thin-film silicon nitride.

Keywords: Micromachined Thermal Sensor, Thin-Film Thermal Conductivity, PECVD Silicon Nitride

INTRODUCTION

Thermal transducers can be found in a vast number of applications ranging from standard temperature sensing to high-precision pressure or flow velocity measurements. By taking advantage of modern micromachining technology, which facilitates the fabrication of small, thermally isolated areas like cantilevers, micro–bridges, or thin membranes serving as the actual sensing region, the sensitivity of such devices can be increased considerably while the response time is decreased at the same time. However, thermal shunts are inevitable and thus always affect the measurement signal. To estimate the extent of this unwanted effect or even compensate for it by using an appropriate model, the corresponding thermal material properties have to be known. However, material data for thin-films can differ considerably from those obtained for bulk matter. Moreover the values stated in different literature sources frequently exhibit serious deviations. For instance, the thin-film thermal conductivity of silicon nitride manufactured by plasma enhanced chemical vapor deposition (PECVD) is determined to be 2.23 Wm^{-1}K^{-1} in [1] whereas a value of 4.50 Wm^{-1}K^{-1} is reported in [2]. On the one hand this deviation can be attributed to the fact, that slight variations in the material composition or the process parameters during the fabrication may change the thermal material properties considerably. On the other hand thermal properties can be burdened with uncertainty since the measurement is falsified by spurious effects, like e.g. radiation, which are not considered by the mathematical model used for the interpretation of the measurement data.

In this contribution, a micromachined cantilever device is presented, which enables to directly determine the thermal conductivity of dielectric thin-films from a single steady-state measurement.

SENSOR DESIGN

The developed structure consists of a thin silicon nitride cantilever with a thickness of d=1.3 µm, which is supported by a silicon frame. On the tip of the cantilever a chromium heater (H) is located close to a highly sensitive amorphous germanium thermistor (CT1). At half the distance between the heater and the silicon frame, a second thermistor (CT2) is arranged on the cantilever. A third thermistor (ST) located at the base of the cantilever provides the opportunity of determining the temperature on the bulk substrate, which is close to the ambient temperature (see Figure 1 and Figure 2).

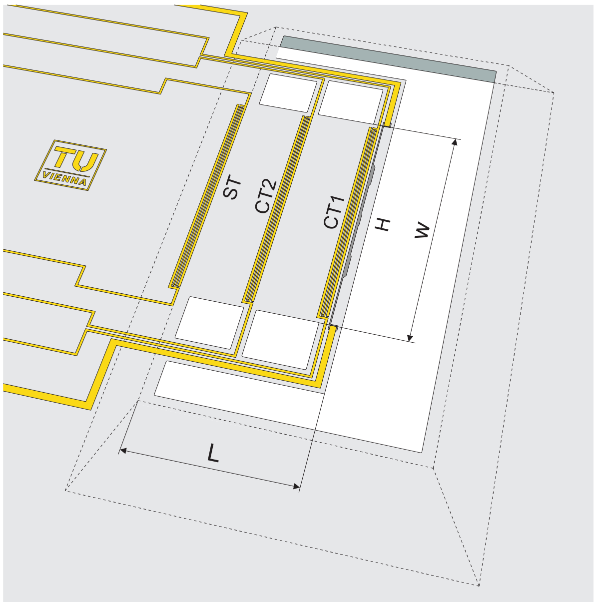

Figure 1. Schematic picture of the cantilever device (L=615 µm, w=1080 µm and 830 µm, respectively).

Amorphous germanium has been used because of its very high resistive temperature coefficient (TCR). Figure 3 depicts the resistance of a highly sensitive germanium thermistor versus the temperature T. Around room temperature the thermistors feature a TCR of about -1.8%/K, which is almost five times higher than the TCR of a platinum resistance temperature detector.

Figure 2. Photomicrograph of the cantilever device.

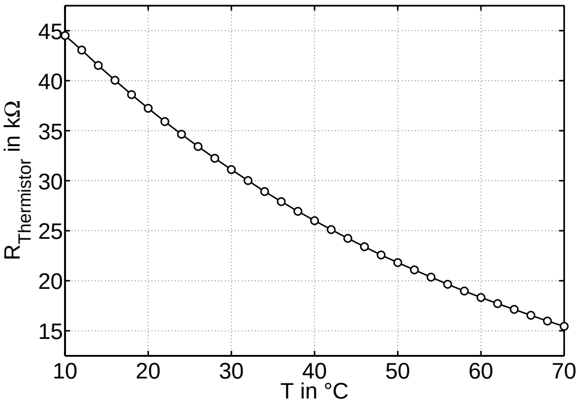

Figure 3. Measured resistance of the germanium thermistor $R_{thermistor}$ versus temperature T. Around room temperature the TCR of the thermistor is about -1.8%/K.

To minimize their influence on the measurement, the connection leads are spatially separated from the actual sensing region by means of lateral ″arms″. Still, these arms result in a temperature distribution featuring a maximum in the center of the heater and decreased excess temperatures at the lateral edges. To avoid this spurious effect, H and CT1 could be covered with a layer featuring a high thermal conductivity serving as ″temperature uniformizer″ [1]. However, the application of such a film would inevitably increase the manufacturing effort involved. In order to avoid additional steps in the fabrication process but to still guarantee a reasonably uniform temperature distribution over the cantilever width, the thickness of the heater structure is chosen to be non-uniform. The geometry of the heater has been defined based on numerical simulations using the finite element software FEMLAB.

Figure 4 shows the temperature distribution over the thermistor CT1 for (i) a heater with uniform and (ii) particular non-uniform thickness, respectively. It can be seen, that in the former case the temperature is distributed Gaussian-like, i.e., exhibits a maximum in the centre and decreases towards the lateral edges of the thermístor. Here, centre and edge temperature differ by about 20%. In the latter case, however, by properly varying the heater thickness, the temperature distribution becomes much more uniform. Consequently the temperature variations over the thermistor are reduced to less than 6%.

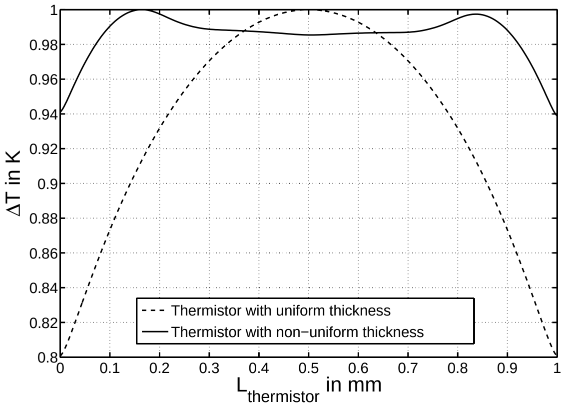

Figure 4. Temperature distribution over the thermistor CT1 for a heater with uniform and non-uniform thickness, respectively.

FABRICATION

To fabricate the micromachined sensor chip, a 350 µm thick (100) silicon wafer has been polished and coated with 320 nm silicon nitride (Si_3N_4) on both sides. First, a 250 nm thick layer of germanium has been vapor-deposited and structured using lift-off technology to form the thermistors. Next, a 130 nm thick layer of chromium has been applied and structured to create the heater. Subsequently, a titanium-gold-chromium layer featuring a thickness of 50-100-30 nm has been deposited and structured to obtain interdigitated electrodes for the thermistors, and connection leads to the bonding pads for heater and thermistors. Then, a low stress silicon nitride (SiN_x) protective film with a thickness of about 1000 nm has been applied using low temperature plasma enhanced chemical vapor deposition (PECVD). Here, the low deposition temperature prevents the germanium film from recrystallization. After creating the apertures for the bonding pads and the backside etch window by means of reactive ion etching, thin membranes have been manufactured using a KOH based anisotropic backside wet etching process. In order to obtain the required cantilevers, the membranes have then been structured from the frontside using a reactive ion etching process. Finally, the chromium has been removed from the bond pads by means of a wet-etching. Consequently, the micromachined cantilevers feature an overall thickness of about 1.3 µm.

MEASUREMENT PRINCIPLE

When the constant power *P* is dissipated in the heater H, the corresponding excess temperature at CT1 with respect to substrate temperature is given by

$$\Delta T = \frac{P - P_{rad}}{G_{cantilever} + 2G_{arm}} \tag{1}$$

where G is the thermal conductance of the entire device, and $G_{cantilever}$ and G_{arm} denote the thermal conductance of the cantilever and of one ″connection lead arm″, respectively. The measurements are conducted in vaccum ($p<10^{-5}$ mbar), thus conductive and convective heat transfer through the surrounding space are negligible and $G_{cantilever}$ results to $\lambda \cdot w \cdot d/L$, were λ is the thermal conductivity of the silicon nitride sandwich, w the width of the cantilever, d its thickness, and L the distance between heater and bulk substrate (see Figure 1). The net rate of radiative heat transfer from the sensor to the surrounding, i.e., the difference between thermal power that is released by the sensor due to radiative emission and the one gained on the basis of radiative absorption from the surrounding, P_{rad}, can be estimated by the Stefan-Boltzmann law

$$P_{rad} = \varepsilon\sigma A\left(T_{sensor}^4 - T_{surrounding}^4\right) \tag{2}$$

Here ε denotes the emissivity of the surface, σ the Stefan-Boltzmann constant (5.671×10^{-8} $\mathrm{Wm^{-2}K^{-4}}$), A the surface area of the sensor, T_{sensor} the sensor surface temperature, and $T_{surrounding}$ the temperature of the surrounding. According to [3], the emissivity of thin-film silicon nitride around room temperature can assumed to be 0.2. From the numerical simulations we obtain that the mean temperature of the cantilever is about 39% of its maximum excess temperature.

By measuring two structures featuring different widths w_1 and w_2 but exhibiting identical ″connection lead arms″, G_{arm} can be eliminated and the thermal conductivity can be calculated by

$$\lambda = \frac{L}{d\left(w_1 - w_2\right)}\left(\frac{P - P_{rad,1}}{\Delta T_1} - \frac{P - P_{rad,2}}{\Delta T_2}\right) \tag{3}$$

where ΔT_1 and ΔT_2 denote the steady-state excess temperatures for structures featuring widths w_1 and w_2, respectively.

MEASUREMENT SETUP

The measurements were carried out in a vaccum chamber at room temperature. To determine the thermal conductivity of the cantilever material only, the steady state excess temperature at CT1 is required which may for instance be determined utilizing a digital multimeter. However, to be able to record the temporal evolution of the temperatures and hence have the opportunity to additionally extract the thermal diffusivity of the thin-film, a PC with a data acquisition board was used in combination with interface electronics (see Figure **5**). Thin-film chromium exhibits a very low resistive temperature coefficient of less than 0.04%/K around room temperature. Applying a constant voltage to the heater structure thus results in a virtually constant power dissipation avoiding the need for a control circuit. In order to read out the thermistor temperature, a DC voltage of 0.5 V is applied. The resulting current is transformed into a corresponding voltage using a current–to–voltage converters.

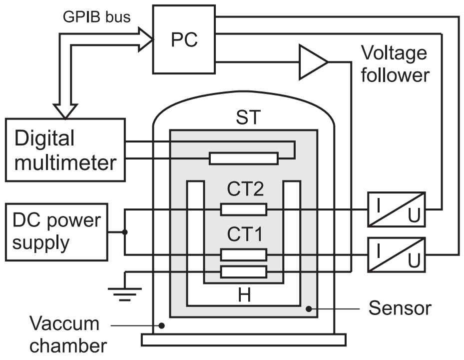

Figure 5. Measurement setup.

For the measurements two different devices with the widths w_1 and w_2 of 1080 µm (geometry 1) and 830 µm (geometry 2), respectively, were utilized. In both cases the applied heater voltage was chosen in a way, that the resulting heating power was 30 µW. Using Eq. (2), the resulting radiative heat losses from the sensor geometries 1 and 2 to the surrounding $P_{rad,1}$ and $P_{rad,2}$ result to 3.04 µW and 3.01 µW, respectively, at room temperature.

RESULTS AND DISCUSSION

Figure 6 shows the temporal evolution of the thermistor excess temperatures ΔT for the different cantilever geometries 1 and 2 over time t. As expected, the thermistors located directly adjacent to the heater CT1 immediately respond to an implied temperature step whereas the thermistors CT2 placed in some distance to the heater exhibit a certain delay time. In combination with the FE model used to define the shape of the heater structure, this temporal evolution can be utilized to determine the thermal diffusivity of the cantilever material. However, the thermal conductivity of the thin-film may directly be calculated from the steady-state excess temperatures using Eq. (3).

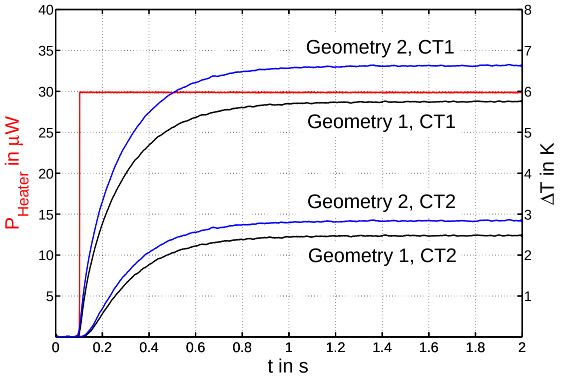

Figure 6. Excess temperature ΔT for cantilevers featuring a width of 1080 µm (geometry 1) and 830 µm (geometry 2) after applying a constant heating power of 30 µW.

The measured final values of 5.748 K and 6.627 K, respectively, yield a thermal conductivity of 1.18 $\mathrm{W/m^{-1}K^{-1}}$ for the measured silicon nitride.

Since the bigger part of the cantilever is made of low temperature PECVD nitride, we accordingly obtain a lower thermal conductivity value compared to data reported for high temperature thin-film silicon nitride in literature [1,2].

This result confirms the assumption that thermal material properties for thin-film must not be considered as universally valid, but are strongly process dependent.

SUMMARY AND CONCLUSIONS

In this contribution a miniaturized sensor was presented which allows to directly determine the thermal conductivity of thin films from a single measurement. The device features a micromachined cantilever consisting of the material under investigation. At the top of this cantilever a heater structure and a highly sensitive germanium thermistor are located. By applying a constant heating power and measuring the resulting steady-state excess temperature at the thermistor, the material's thermal conductivity was derived using a simple analytical model. For low temperature PECVD silicon nitride a thermal conductivity of 1.18 $W/m^{-1}K^{-1}$ was obtained. This value is clearly lower compared to the literature data reported for standard PECVD nitride ranging from 2.23 $Wm^{-1}K^{-1}$ to 4.50 $Wm^{-1}K^{-1}$. This can be attributed to the different processes parameters used for fabricating the thin films.

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