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Ultrasensitive string-based temperature sensors

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Resonant strings are a promising concept for ultra sensitive temperature detection. We present an analytical model for the sensitivity with which we optimize the temperature response of resonant strings by varying geometry and material. The temperature sensitivity of silicon nitride and aluminum microstrings was measured. The relative change in resonant frequency per temperature change of $-1.74 \pm 0.04\%/{}^\circ\mathrm{C}$ of the aluminum strings is more than one order of magnitude higher than of the silicon nitride strings and of comparable state-of-the-art AuPd strings. © *2011 American Institute of Physics*. [doi:10.1063/1.3567012]

Temperature is one of the most frequently measured physical quantities in industry and research. Chemical reaction rates, refractive indexes, resistivities, etc., are temperature dependent and require the precise measurement of temperature. In particular, accurate temperature detection is required in applications such as in high-sensitivity microfluidic calorimeters.[1] Temperature is commonly measured by means of thermocouples, resistance temperature detectors (RTDs), or thermistors.[2] Thermocouples are based on the Seebeck effect and measure the temperature difference between a hot and a cold junction. RTDs and thermistors are based on the change in resistivity of a metal or a semiconductor, respectively, as a function of temperature. In comparison to thermocouples, RTDs and thermistors allow absolute temperature measurements. A temperature resolution as low as 3×10^{-5} °C has been achieved with vanadium oxide (VO_x) thermistors.[3] Unfortunately, VO_x is toxic and it is difficult to precisely control the oxidation state and electrical properties.[4]

In this paper we investigate the temperature response of resonant microstrings and nanostrings. The combination of extraordinary high quality factors[5] and a high temperature sensitivity[6] makes resonant strings highly interesting structures for ultrasensitive absolute temperature sensing. Fundamental understanding of the temperature response of resonant strings is crucial for the optimal design of the sensors. We present an analytical model for the sensitivity with which we optimize the temperature response of resonant strings by varying geometry and material. The strings are fabricated by standard microprocessing of nontoxic materials.

The eigenfrequency of a string with a coefficient of thermal expansion α_{str} fixed on a substrate with α_{sub} as a function of temperature T can be described by:[6]

$$f_0(T) = \frac{n}{2L}\sqrt{\frac{\sigma_0 - E(\alpha_{str} - \alpha_{sub})(T - T_0)}{\rho}} n = 1,2, \ldots , \tag{1}$$

where n is the mode number, σ_0 the tensile stress at T_0, L is the length, E Young's modulus, and ρ the mass density of the string. In this model, temperature induced changes in Young's modulus, density, and length of the string are neglected.

The temperature sensitivity S at T_0 of a string-based sensor is then given by

$$S = \left.\frac{\partial f_0}{\partial T}\right|_{T=T_0} = -\frac{nE(\alpha_{str} - \alpha_{sub})}{4L\sqrt{\rho\sigma_0}}. \tag{2}$$

The temperature sensitivity (2) is investigated by means of low stress silicon rich silicon nitride and aluminum microstrings as shown in Fig. 1. The silicon nitride strings are 15 μm wide, 177 nm or 340 nm thick, and the length varies between 114 and 1579 μm. The aluminum strings are 3 μm wide, 30 nm thick, and 200 μm long. The fabrication of the strings is described elsewhere.[7,8]

The resonant frequency of the strings was determined in high vacuum at a pressure below 3×10^{-5} mbar with a laser-Doppler vibrometer (MSA-500 from Polytec GmbH) by measuring the thermal noise resonance peaks of the first

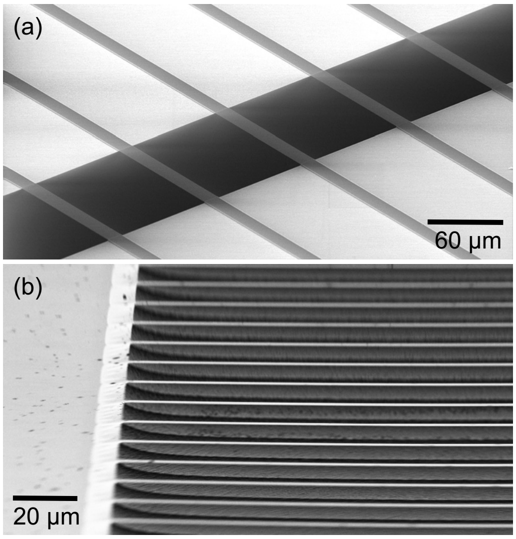

FIG. 1. (a) SEM micrograph of 114 μm long, 340 nm thick, and 15 μm wide silicon nitride strings. (b) SEM micrograph of 200 μm, 3 μm wide, and 30 nm thick Al strings.

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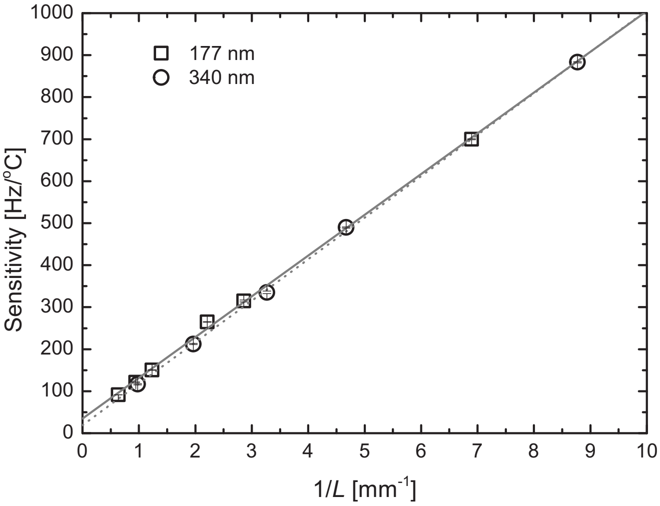

FIG. 2. The measured frequency shift per degree Celsius of silicon nitride strings of various lengths. The error bars are the standard deviation. The solid and dotted lines are linear fits to the points from the 177 nm and 340 nm thick strings, respectively.

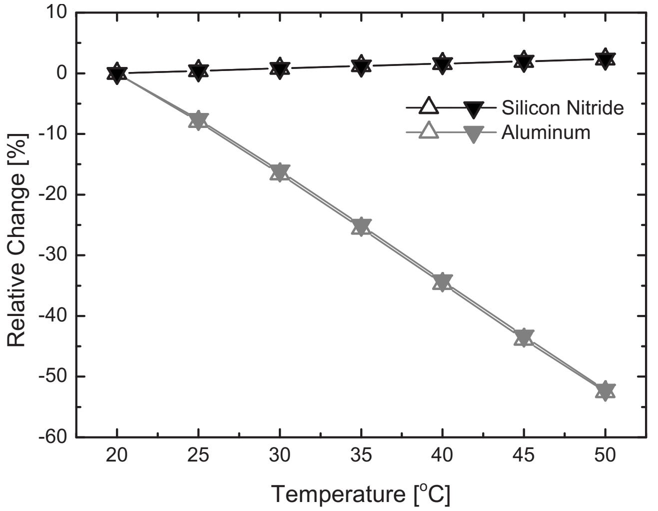

FIG. 3. Relative frequency shift of a 214 μm long and 340 nm thick silicon nitride string and a 200 μm aluminum string as a function of temperature. The resonance frequency at 20 °C is 627 kHz and 202 kHz for the silicon nitride and aluminum strings, respectively. Hollow and solid symbols represent the measured values as the temperature was swept from 20 °C to 50 °C and 50 °C to 20 °C, respectively.

bending mode. The temperature was controlled with a Peltier element and measured with a thermistor with a temperature resolution of 0.02 at 20 °C. In all the measurements the temperature was cycled between 20 and 50 °C in steps of 5 °C and the temperature was allowed to stabilize before the resonance frequency was measured. The laser introduces a shift in the resonance frequency of the strings which is less than 1%.

The measured resonant frequencies of higher order harmonics are multiples of the first harmonic which represents a distinct stringlike behavior. At 20 °C the resonant frequency of the silicon nitride strings varies from 79 kHz for the longest to 1.24 MHz for the shortest. Assuming a density of 2900 $\mathrm{kg/m^3}$ the average prestress of the 177 nm and 340 nm thick silicon nitride strings is 181.8 MPa ± 1.8 MPa and 205.9 MPa ± 9.8 MPa, respectively. The quality factor is ranging from $\sim 3\times 10^5$ for the shortest strings to $\sim 2.4\times 10^6$ for the longest strings. The average resonance frequency of the aluminum strings at 20 °C was 205.6 kHz ± 8.1 kHz and the quality factor was ~3700. Assuming a density of 2700 $\mathrm{kg/m^3}$ the average prestress is 18.3 MPa ± 1.5 MPa.

According to (2), the sensitivity of a string can be increased be decreasing the length of the string. In Fig. 2, the temperature sensitivity of the silicon nitride strings is shown. For each length and thickness, three strings were analyzed. The plotted error bars show that there is little variation in the performance between strings of the same dimension. The temperature sensitivity varies from 91 Hz/°C for 1579 μm long and 177 nm thick strings to 883 Hz/°C for 114 μm long and 340 nm thick strings. The temperature sensitivity as a function of the inverse length is linear as shown by the fits, in accordance with (2). This shows that the temperature sensitivity of a string can be increased by reducing the length as expected from the model. With a coefficient of thermal expansion of silicon of 2.6 ppm/°C (Ref. 9) and assuming a Young's modulus for silicon nitride of 250 GPa, a coefficient of thermal expansion of silicon nitride of 1.23 ± 0.15 ppm/°C can be calculated from the measured sensitivity of the 33 analyzed strings.

Beside of using short strings, the sensitivity (2) can be further improved by choosing a string material with a high Young's modulus, high thermal expansion difference to the substrate, low density, and low prestress. Aluminum is a better string material compared to silicon nitride due to the higher thermal expansion and typically lower prestress in deposited thin films. Therefore the temperature sensitivity of six aluminum strings was analyzed. In Fig. 3, the relative frequency shift in a silicon nitride and aluminum string is plotted as a function of the temperature. Since the coefficient of thermal expansion of aluminum is higher than for silicon the slope of the curve is negative. The average frequency shift per degree temperature change in the aluminum strings is −3517 ± 83 Hz/°C. Assuming a thermal expansion coefficient of 23 ppm/°C,[10] a Young's modulus of 30.7 ± 0.7 GPa for the aluminum thin film can be calculated. The modulus of sputtered aluminum is known to depend on the fabrication process and corresponds to reported values.[11] Thus an improved aluminum deposition process would increase the Young's modulus which, according to (2), would result in a higher temperature response.

In Table I the measured temperature sensitivity of the strings are compared to state-of-the-art AuPd (Ref. 12) and SU-8 (Ref. 6) strings. The relative frequency shift per temperature change in aluminum strings is more than one order

TABLE I. The resonance frequency, prestress, frequency shift per temperature change, and relative change in four different strings. The listed resonance frequencies are measured at 20 °C.

	f_{res} (kHz)	σ_0 (MPa)	$\Delta f/\Delta T$ (Hz/°C)	$R\%$ (%/°C)
AuPd[a]	~133	296	−164	−0.12
SU-8[b]	~214	20	−1090	−0.51
$\mathrm{SiN_x}$	627	209	+491	+0.08
Al	202	17.6	−3517	−1.74

[a] Reference 12.
[b] Reference 6.

of magnitude higher than for the silicon nitride and AuPd strings. This is mainly due to the lower prestress and higher thermal expansion coefficient. Compared to the SU-8 strings, the relative change is three times higher. This is mainly due to the higher Young's modulus of aluminum. SU-8 strings show relaxation and aging effects[6] which cause frequency drifts which are unfavorable for sensor applications.

The measured strings have exceptionally high quality factors which results in a high frequency resolution. Naik *et al.*[13] have demonstrated a frequency resolution of $6 \times 10^{-5}\%$ for nanomechanical beam resonators in high vacuum. With this frequency resolution the silicon nitride and aluminum strings allow for detection of temperature changes of 6.67×10^{-4} °C and 3.4×10^{-5} °C, respectively. By optimizing the deposition process of the aluminum with regard to the mechanical properties and lowering the prestress to for instance 10 MPa, it should be possible to detect temperature changes of 8×10^{-6} °C.

It has been demonstrated that string-based temperature sensors is a promising concept. Strings can be realized through standard fabrication and with standard materials. The study of the silicon nitride strings showed that the sensitivity can be increased by reducing the length. The aluminum strings proved the importance of material combination and the amount of prestress. A relative temperature sensitivity of $-1.74 \pm 0.04\%/°\text{C}$ was measured for the aluminum strings which is more than one order of magnitude higher than reported values for a comparable device.

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