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A Micromechanical Sensor of Temperature Based on Surface Plasmons Resonance

[a]Juriy HASTANIN, [a]Yvon RENOTTE, [b]Karl FLEURY-FRENETTE, [a,b]Serge HABRAKEN

[a] Université de Liège, Physics Department, HoloLab, Liège, Belgium, B-4000
[b] Centre Spatial de Liège, Liège, Angleur, Belgium, B-4031
Tel.: ++32-4-3663649 / ++32-4-3663772, fax: ++32-4-3664516
E-mail: urahast@yahoo.com

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Abstract: This paper reports a new concept of micromechanical sensors of temperature. The sensors consist of a micro-cantilever transducer and optical readout means for monitoring cantilever mechanical response using the surface plasmons resonance (SPR) phenomenon. This solution has the advantage of reducing the cantilever length due to an ultrahigh resolution of the optical readout means and, therefore a high signal-to-noise ratio can be achieved. *Copyright © 2008 IFSA.*

Keywords: Surface plasmons, Cantilever sensing, MOEMS

1. Introduction

The temperature sensing is a key tool in vast variety of applications ranging from environmental monitoring to biomedical diagnostics, and thermal probing of active microelectronic devices, [1-3].

The recent development of Micro-Opto-Electro-Mechanical Systems (MOEMS) technology makes very attractive the Micro-Mechanical Temperature Sensors (MMTS), because of their numerous advantages, such as a high sensitivity and durability in aggressive environment (for example, at a high level of radioactivity and at a high temperature).

The design of the micromechanical temperature sensors varies according to the nature of the environment and the required measurement precision. In any case, a micromechanical temperature sensor consists of two parts: an element designed to transduce an environment temperature change into a mechanical movement, such as a micro-cantilever, and readout means to measure the extent of this movement.

The most commonly MMTS transducing principle involves well-known bimetallic effect. In this case, the thermometer transducer is a bimorph micro-cantilever, which bends according to a temperature change. The cantilever deflection is proportional to the temperature change of the beam and also to the difference between the Coefficients of Thermal Expansion (CTE) of the two cantilever layers. Theoretical evaluation providing an analytical expression for a rectangular bimorph cantilever tip bending ΔZ as a function of its temperature change ΔT was reported, for instance by [3]. This expression is written as follow:

$$\Delta Z = \frac{3\, n\, b_1\, b_2\, h_1\, h_2\, (h_1 + h_2)(\beta_1 - \beta_2)}{\left(b_1\, h_1^2\right)^2 + \left(n\, b_2\, h_2^2\right)^2 + n\, b_1\, b_2\, h_1\, h_2\, \left(4h_1^2 + 6h_1\, h_2 + 4h_2^2\right)} \cdot L^2 \cdot \Delta T\,, \tag{1}$$

where $n=E_2/E_1$; L is the length of the cantilever; h_k, β_k and E_k are the thickness, CTE and the modulus of elasticity of the layer k, respectively.

It is important to note that the resolution of the bimorph cantilever transducer is limited by a thermal vibration noise, known as thermodynamic fluctuation noise presented in any thermodynamic system due to random temperature fluctuations. This noise increases with the cantilever length since its spring constant is decreasing. On the other hand, the total resolution of the temperature sensor will have contributions from both cantilever thermal sensitivity and readout method resolution. Consequently, in order to improve the total sensitivity and the resolution of the temperature sensor, a high resolution of the readout means must be provided.

A high sensitive bending measurement can be achieved via electronic [3] and optical methods [1, 2]. The optical methods, compared to the electronic ones, have several advantages, such as simplicity, better linearity of response, reliability in aggressive environment and at high temperatures.

The mostly common ultrahigh resolution optical readout techniques involve the interference/diffraction phenomena and the reflected light beam deviation principle. However, the first method does not support real-time operation because a translating processing is necessary to obtain an interferogram [4], whereas the latter method would require at least two photo-detectors for a single micromechanical transducer, which constitutes an obvious drawback for the manufacturing of two-dimensional cantilever-based sensor arrays.

In this paper we demonstrate a new optically based method for the monitoring of temperature sensor cantilever deflection with the resolution in the nanometer range that does not suffer from these drawbacks.

2. Readout Principle

The proposed sensing principle involves a measure of the metallic thin film reflectance change due to a change of Surface Plasmons (SPs) excitation efficiency induced by micro-cantilever thermal bending. The working principle is illustrated in the Fig. 1 and 2.

The temperature sensor includes a TM (Transverse Magnetic) polarized light wave source, an optical coupling means (a prism or a micro-structured grating) for optical coupling of the light wave with surface plasmons propagated into a multilayer system composed of a metallic thin film (typically, silver or gold) and a micro-cantilever (see Fig. 1). The incident angle of the light wave is fixed and optimized such that the excitation of surface plasmons is efficiently produced (resonance).

A cantilever bending to be measured changes the thickness of the gap between the lower surface of the cantilever and the metallic thin film. It will result in a shift of the surface plasmons light excitation efficiency. As a result, the conversion of the incident light energy in SPs mode energy is substantially worse and, consequently, the reflectance of a metallic thin film increases (see Fig. 2).

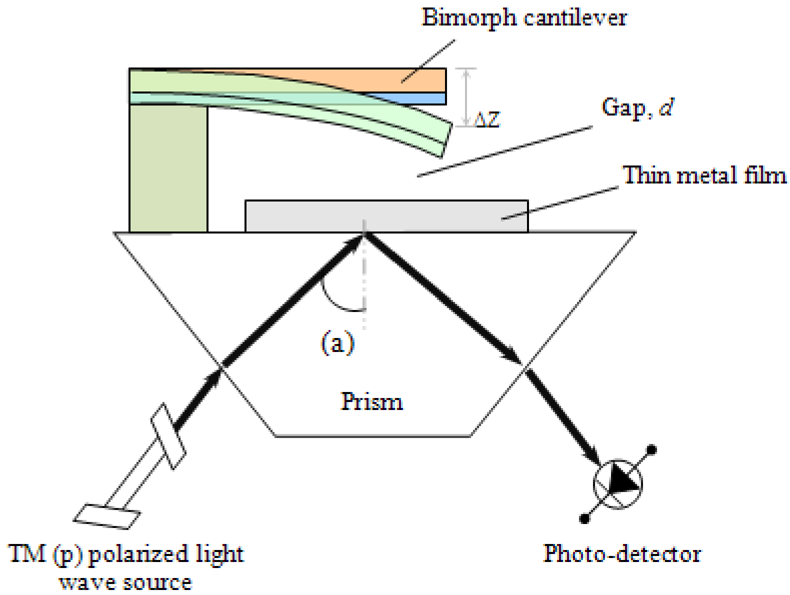


Fig. 1. The schematic view of the SPR micromechanical sensor of temperature (not in scale: Z scale is exaggerated for clarity).

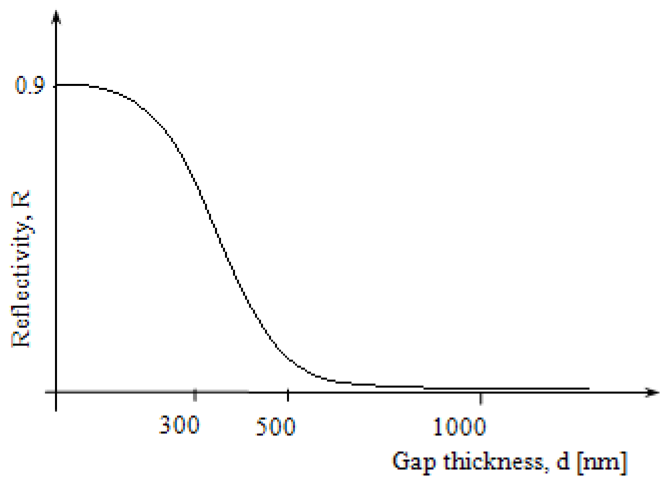


Fig. 2. Simulation of the reflectivity vs. thickness of gap.
Design parameters: θ=44.38°; metal (gold) film thickness is 49nm; the prism refractive index n_{prism}=1.50; the index of the lower layer of the cantilever n=1.40; light source wavelength is 632.8 nm.

3. Surface Plasmons Resonance and Multilayer Reflectivity Calculation

The surface plasmons are charge density longitudinal oscillations of the free electron gas on the interface between a metal and a dielectric medium. Surface plasmons can be excited by TM-polarized light wave at a specific incident angle wherein the tangential component of its wave vector matches the SPs wave vector, k_{sp}. As a result, the light intensity reflected by metallic film depicts a sharp dip at this angle. This phenomenon commonly is referred as Surface Plasmons Resonance (SPR), [5-8].

The most common ways of exciting SPs involve the Attenuated Total Reflection (ATR) and the grating coupling techniques, [5].

Fig. 1 shows an example of the most common practical implementation of the ATR technique referred as Kretschmann–Raether ATR configuration. In this case, the light wave incident angle, wherein the resonance conditions are fulfilled (therefore, the SPs can be generated) is close to, [5-8]:

$$\theta_{SPR} \approx arcsin\left(n_0^{-1} \sqrt{\frac{\varepsilon_r(\omega)\cdot\varepsilon_1}{\varepsilon_r(\omega)+\varepsilon_1}} \right), \tag{2}$$

where n_0 is refractive index of the prism, $\varepsilon_r(\omega)$ is the real part of the dielectric function of the metal and ε is the dielectric function of the adherent dielectric medium being in contact with the metallic film.

In the range of visible wavelengths, the resonance condition can be fulfilled by noble metals like gold and silver, [5-8].

It is important to note that the resonance angle and the reflectivity dip shape extremely depend on the refractive index and the thickness of the layer adjacent to the metal layer surface supporting the SPs. In our case, this feature enables to measure the thickness of the gap (see Fig. 1) with a very high precision and, consequently, the micro-cantilever bending can be monitored with a high resolution.

We intend to present the basis of the sensor performance modeling.

The temperature sensor can be represented as a multilayer system shown in Fig 3 (commonly, as a four- layer sandwich). Therefore, the change in multilayer reflectivity versus the gap thickness changing (induced by the cantilever bending) can be calculated by using the well know transfer matrix algorithm for multilayer systems, [6].

The Maxwell's equations boundary conditions imply that the tangential components of the electric and magnetic fields as well as the normal components of the dielectric displacement and the magnetic induction are conserved at an interface between the layers.

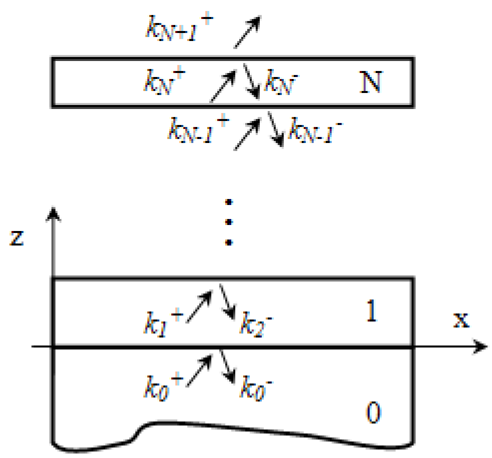


Fig. 3. Geometry and conventions used for the sensor modeling.

The SPR multilayer system reflectivity shown in Fig. 3 can be calculated by applying this requirement to each layer boundary *n*. It leads to the matrix relation, [6]:

$$\begin{bmatrix} E_{0,x}^{+} \\ E_{0,x}^{-} \end{bmatrix} = \prod_{n=0}^{n=N} [M_n] \times \begin{bmatrix} E_{N+1,x}^{+} \exp\left(-i\, k_{N+1,z}^{+}\, z_{N+1}\right) \\ E_{N+1,x}^{-} \exp\left(+i\, k_{N+1,z}^{-}\, z_{N+1}\right) \end{bmatrix}, \quad (3)$$

where the transfer matrix of a layer *n* can be written as:

$$M_n = \begin{bmatrix} \dfrac{(u_n + u_{n+1}) \exp\left(i\, k_{n,z}^{+}\, d_n\right)}{2\, u_n} & \dfrac{(u_n - u_{n+1}) \exp\left(i\, k_{n,z}^{+}\, d_n\right)}{2\, u_n} \\ \dfrac{(u_n - u_{n+1}) \exp\left(-i\, k_{n,z}^{-}\, d_n\right)}{2\, u_n} & \dfrac{(u_n + u_{n+1}) \exp\left(-i\, k_{n,z}^{-}\, d_n\right)}{2\, u_n} \end{bmatrix}, \quad (4)$$

The quantity u_n for a layer *n* is given by:

$$u_n = \frac{\varepsilon_n}{k_{n,z}}, \quad (5)$$

with the normal components of the vector $k_{n,z}^{+}$:

$$k_{n,z}^{+} = k_{n,z}^{-} = \pm\sqrt{\varepsilon_n \left(\frac{2\pi}{\lambda}\right)^2 - k_{0,x}^2}\ , \quad (6)$$

where the tangential component of light wave vector in the prism is given as:

$$k_{0,x} = \frac{2\pi}{\lambda}\, n_0 \sin\theta, \quad (7)$$

In these equations ε_n, d_n, λ and θ are, respectively, the permittivity and thickness of the layer *n*, the radiation wavelength in vacuum and the incident angle; the tangential and normal components of the vectors is denoted, respectively, by the subscripts *x* and *z*; E_m and k_m denote, respectively the electric field vectors and light wave vectors. The incident and reflected waves are denoted, respectively, by the superscripts + and **-**.

Thus, if all optical parameters (ε_n and d_n) are known, each layer transfer matrix as well as the transfer matrix product in Eq. (3) can be calculated.

Finally, the total reflectivity of the multilayer system can be evaluated as:

$$R \equiv \frac{\mathrm{M}_{21}}{\mathrm{M}_{11}}, \quad (8)$$

To conclude, the set of equations (3-8) is the basis for the numeric computation of the SPR reflectivity curves for any type of multilayer configuration. Consequently, the amount of the cantilever bending producing the reflectivity change can be calculated.

In order to estimate the gap thickness measurement resolution we must choose a resolution criterion (*otherwise, a decision rule that corresponds to the apparatus working principle*). In our case, in first approach, we use a criterion based on the contrast threshold principle. That means that in order to detect a reflectivity change induced by the cantilever bending, it must be in excess of a certain threshold. The typical value of the contrast threshold C_0 at low light levels, as depicted by the Rayleigh criterion, is about 10%, [9].

It is helpful to note that the image contrast is a dimensionless quantity. Therefore, in our case, it can be expressed in terms of multilayer system reflectivity as:

$$C = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}}, \tag{9}$$

where R_{max} and R_{min} are maximal and minimal reflectivities, respectively.

Since we intend to demonstrate the ultimate sensor sensitivity, we consider only very small change of reflectivity, $\Delta R = R_{\max} - R_{\min}$.

Consequently, we can assume that:

$$C \approx \frac{\Delta R}{2R_a}, \tag{10}$$

where R_a is the reflectivity corresponding to the image-average intensity.

Then the minimal detectable reflectivity change can be expressed as:

$$\Delta R \approx C_0\ 2R_a \approx 0.2R_a, \tag{11}$$

4. Results

Computer simulations are helpful to predict and to optimize the performance and the experimental realization of SPR micromechanical sensors. In this section we give some quantitative results for bimorph cantilever-based thermometer reported in Ref. [3] with SPR readout in the Kretschmann-Raether ATR configuration. The gold/silicon cantilever used in this thermometer is shown in Fig. 4. The geometrical and material proprieties of the cantilever are given in Table 1.

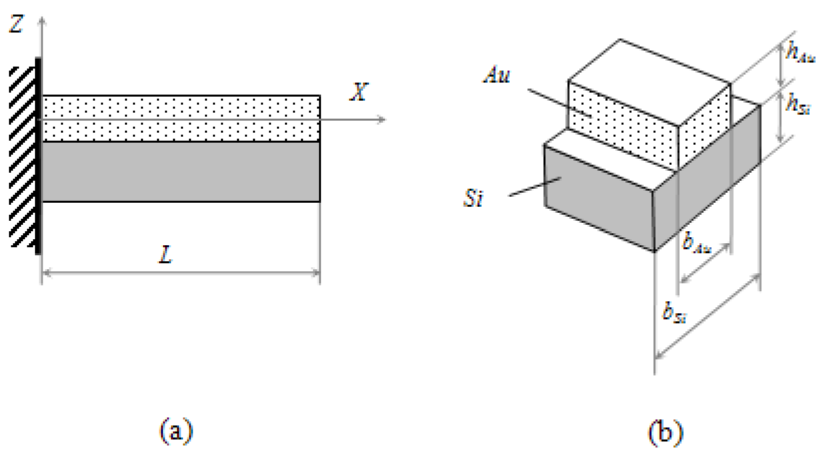


Fig. 4. Sketch of the temperature sensor bimorph cantilever, [3]: lateral (a) and section (b) views.

Table 1. Geometrical and material proprieties of the gold/silicon cantilever thermometer.

Parameter	Value
β_{Au}	$14.3 \cdot 10^{-6}$ K^{-1}
β_{Si}	$2.6 \cdot 10^{-6}$ K^{-1}
E_{Au}	$80 \cdot 10^{9}$ Nm^{-2}
E_{Si}	$122 \cdot 10^{9}$ Nm^{-2}
h_{Au}	1.8 μm
h_{Si}	4 μm
b_{Au}	80 μm
b_{Si}	100 μm
L	500 μm

Substituting this set of parameters into Eq. (1) gives the thermo mechanical sensitivity of the cantilever (*see also in* [3]):

$$S_{cantilever} = \frac{\Delta Z}{\Delta T} \approx 270 \ \ nm/K, \tag{12}$$

Simulation results are shown in Fig. 5, in which the reflectivity dip due to SPR is calculated for three gap thicknesses. Fig. 6 (a-b) shows the reflectivity as a function of the gap thicknesses. The design parameters of SPR readout used in calculation are given in Table 2.

Table 2. Parameters of the SPR readout means.

Parameter	Value
Dielectric function of gold, ε_{Au}	-11.547+1.2i
Gold film thickness, d_{Au}	40 nm
Gap thickness, d	567 nm
Light wavelength, λ	633 nm
Prism refractive index, n_0	1.515

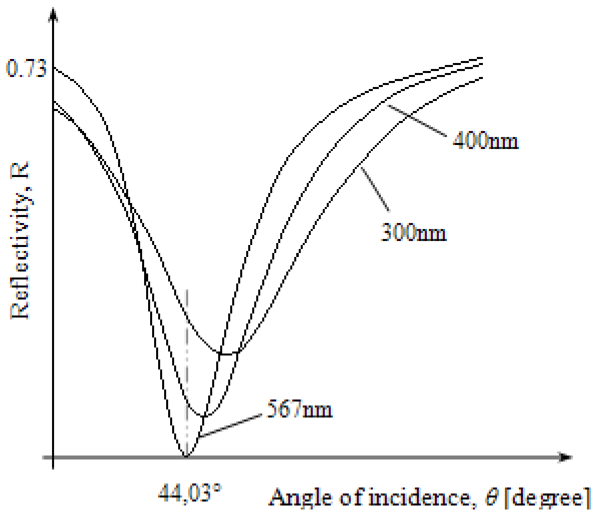


Fig. 5. Simulation of reflectivity vs. incidence angle calculated for various thicknesses of gap.

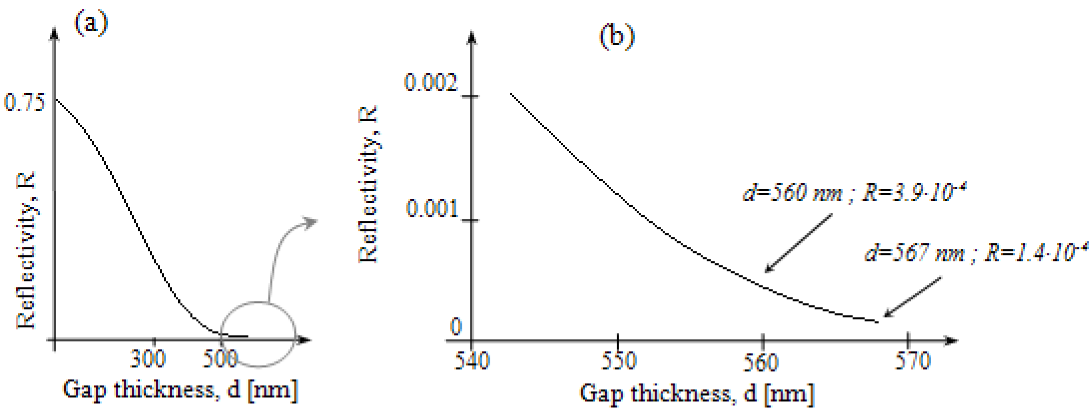


Fig. 6. Simulation of reflectivity vs. thickness of gap calculated for incidence angle corresponding to the SPR dip position of the system prism/metal/air/Si: (a) overall view and (b) enlarged view for the gap thickness ranging from 540 to 567 nm.

The calculated multilayer reflectivity at the gap thickness 567 nm is about $1.4\cdot10^{-4}$. This value corresponds to the image-average intensity. Assuming a typical value of the contrast threshold about 10%, according to the Eq. (11), a reflectivity change of about $0.28\cdot10^{-4}$ is detectable. The numeric simulation shows that the derivative of the reflectivity with respect to the gap thickness is about $0.357\cdot10^{-4}$ nm^{-1}. Consequently, by using a linear fitting of reflectivity curve, we can calculate the minimal detectable gap thickness change as:

$$\Delta d \approx 0.28\cdot10^{-4} / 0.357\cdot10^{-4} \approx 0.8\, nm . \tag{13}$$

Using the design parameters of SPR readout mentioned above, the sensor reaches a gap thickness resolution close to 0.8 nm. Thus, the micromechanical thermometer using bimorph cantilever referred in [3] has the measured resolution close to

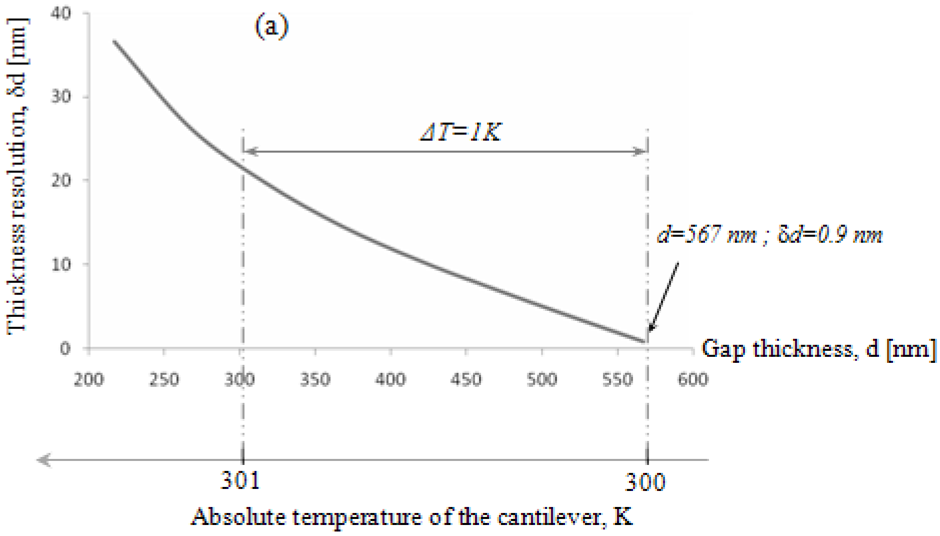
$$\Delta T = \frac{0.8\, nm}{270\, nm / K} \approx 3\cdot10^{-3}\ K .$$

Finally, it is important to note that the gap thickness resolution becomes worse if the cantilever bending is very important (see Fig. 7.a). Therefore, this degradation limits the temperature sensor dynamical range (see Fig. 7.b). To achieve a rational compromise between sensor thermal resolution and its dynamical range, both the cantilever and the SPR readout designs must be carefully optimized. Fig. 7a is also depicting the absolute temperature scale (applying Eq. (12)). We assume sensor calibration based on a gap thickness of d=567nm at T=300K.

5. Conclusions

The main idea of this manuscript was to demonstrate a micromechanical cantilever-based thermometer with high sensitivity obtained due to surface plasmons resonance readout principle. The simulation results show that the cantilever bending can be measured with a resolution in the nanometer range.

The proposed concept provides sensitive temperature sensors useful in very vast variety of applications.



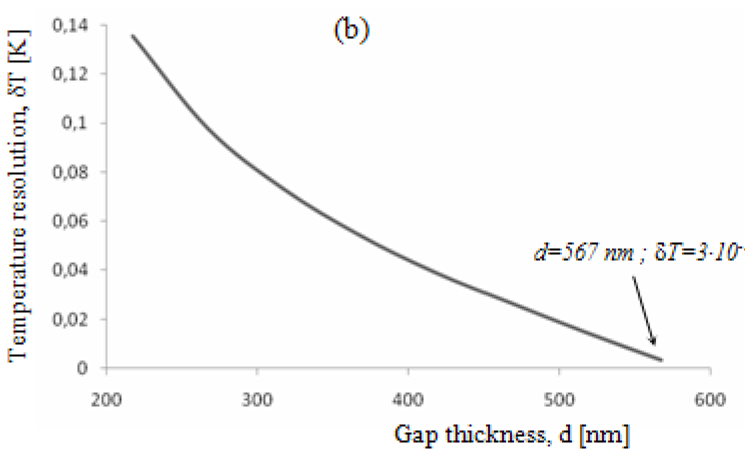


Fig. 7. (a) Simulation of measured gap thickness resolution vs. thickness of gap; (b) Simulation of temperature resolution vs. thickness of gap.

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