Optimized Design of High Sensitivity Micromechanical Photon Detectors

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Abstract. With the rapid development of micro-electro-mechanical system (MEMS) technology, uncooled micromechanical infrared detectors become available and attract more and more attention. This paper first deducts the theory of bilayer cantilever with different stress in each layer, and then applies it to the design of micromechanical photon detectors. This theory is somewhat different from the theory in many literatures because it is based on not surface stress but layer stress. With this theory, optimized design of micromechanical photon detectors can be performed, which includes both material choice and geometry determination. As an example, a high sensitivity silicon-based micromechanical photon detector is designed, which reaches a sensitivity of 47 times larger than conventional designs.

1. Introduction
With the rapid development of micro-electro-mechanical system (MEMS) technology, uncooled micromechanical infrared detectors become available and attract more and more attention [1-6]. Generally, micromechanical infrared detectors can be divided into two categories: detectors based on thermal effect and detectors based on quantum effect, and the last one is called “micromechanical quantum detectors” or “micromechanical photon detectors”. The newly developed micromechanical photon detectors have shown superior performance: high sensitivity, short response time and room temperature work capability. All reported micromechanical photon detectors borrowed theory from Stoney’s relationship or bimetal effect by introducing photo-induced stresses [4-6]. However, since all these theories are deducted on the base of surface stress, they cannot reflect the nature of photo-induced stress as a film stress.

This paper first deducts the theory of bilayer cantilever with different stress in each layer, and then applies it to the design of micromechanical photon detectors.

2. Theory of bilayer cantilever with different stress in each layer
The model of bilayer cantilever with different stress in each layer is illustrated in figure 1. \(L\) and \(w\) are the length and width of the cantilever, \(t_1\) and \(t_2\) are the thickness of layer 1 and layer 2 respectively, \(E_1\) and \(E_2\) are the moduli of the two layers.
Suppose the non-elastic stress in the bilayer is $\sigma_1$ and $\sigma_2$ respectively, then the bending moment caused by these externally induced stresses can be calculated as below:

$$M_n = \int z \sigma dA = w \int_1^2 \sigma_1 z dz + w \int_1^2 \sigma_2 z dz = \left( \frac{\sigma_1}{E_1} - \frac{\sigma_2}{E_2} \right) E_1 w t_1 \left( \frac{t_1 + t_2}{2} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-1} \tag{1}$$

When the bilayer cantilever reaches its balance, this bending moment is equal to the elastic bending moment, therefore we have

$$M_n = -\frac{1}{R} (E_1 I_1 + E_2 I_2) \tag{2}$$

where $R$ is the bending radius, $I_1$ and $I_2$ represent the moment of inertia of layer 1 and 2 respectively, which can be calculated as [7]:

$$I_1 = \frac{wt_1^3}{12} + wt_1 \left( \frac{t_1 + t_2}{2} \right)^2 \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-2} \tag{3}$$

$$I_2 = \frac{wt_2^3}{12} + wt_2 \left( \frac{E_1 t_1}{E_2 t_2} \right)^2 \left( \frac{t_1 + t_2}{2} \right)^2 \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-2} \tag{4}$$

Combining equation (1) - equation (4), the bending radius of the bilayer cantilever can be calculated as:

$$\frac{1}{R} = \frac{M_n}{E_1 I_1 + E_2 I_2} = \left( \frac{\sigma_1}{E_1} - \frac{\sigma_2}{E_2} \right) 6 \left( \frac{t_1 + t_2}{2} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-2} \tag{5}$$

Therefore, the deflection at the end of the bilayer cantilever $\delta$ is given by

$$\delta = \frac{L^2}{2R} = \left( \frac{\sigma_1}{E_1} - \frac{\sigma_2}{E_2} \right) 3L^2 \left( \frac{t_1 + t_2}{2} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-2} \tag{6}$$

3. Photo-induced stress in metal-semiconductor cantilevers

Generally, photo radiation illuminated onto a semiconductor will generate two effects: thermal effect and photon effect, which in turn lead to the thermal stress and electronic stress respectively [4-6]. However, electronic stress caused by excess charge carrier generation occurs only in semiconductor material, while thermal stress caused by temperature change occurs in both metal and semiconductor materials.

Suppose layer 1 is the semiconductor layer and layer 2 is the metal layer, then photo-induced thermal stress in the two layers can be written as:

$$\sigma_{\text{T1}} = E_1 \alpha_1 \Delta T \tag{7}$$

$$\sigma_{\text{T2}} = E_2 \alpha_2 \Delta T \tag{8}$$
where, $\alpha_1$ and $\alpha_2$ are the thermal expansion coefficient of semiconductor and metal, $\Delta T$ represents temperature change.

The photo-induced electronic stress in the semiconductor is:

$$\sigma_{E1} = E_1 \left( \frac{1}{3} \frac{dE_g}{dP} \right) \Delta n$$

(9)

where, $dE_g/dP$ is the pressure dependence of the band gap, $\Delta n$ is the density of photo-generated excess charge carriers, which is given by

$$\Delta n = C_0 \left( 1 - \frac{\lambda}{\lambda_c} \right) \tau_L \Phi^\text{abs}_E$$

(10)

where, $C_0$ is a constant depending on quantum yield and in units of inverse energy, $\lambda$ is the wavelength of the incident photo radiation, $\lambda_c$ is the cut-off wavelength of the metal-semiconductor Shottky barrier, $\tau_L$ is the lifetime of the photo-generated carriers and $\Phi^\text{abs}_E$ is the absorbed energy resulted in charge carrier generation.

4. Optimized design of micromechanical photon detectors

4.1. Equation deduction for optimized design

Micromechanical photon detectors are based on semiconductor-bilayer cantilevers and the bilayer is usually a metal layer. According to the photo-induced stress analysis, in the semiconductor layer the photo-induced stress has two components:

$$\sigma_1 = \sigma_{T1} + \sigma_{E1} = E_1 \alpha_1 \Delta T + E_1 \left( \frac{1}{3} \frac{dE_g}{dP} \right) \Delta n$$

(11)

while the bilayer layer (non-semiconductor) only have thermal stress

$$\sigma_2 = \sigma_{T2} = E_2 \alpha_2 \Delta T$$

(12)

Substituting the $\sigma_1$ and $\sigma_2$ of equation (6) with equation (11) and equation (12), we can obtain the deflection of semiconductor-bilayer cantilevers:

$$\delta = \delta_T + \delta_E$$

(13)

where,

$$\delta_T = (\alpha_1 - \alpha_2) \Delta T \frac{3L^2}{t_1} \left( \frac{t_1}{t_2} + \frac{t_1^2}{t_2^2} \right) \left( 1 + \frac{t_1}{t_2} \right)^2 + \left( \frac{E_2 t_2}{E_1 t_1} + \frac{t_1^3}{t_2^3} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-1}$$

(14)

is the deflection caused by thermal stress, and

$$\delta_E = \frac{dE_g}{dP} \Delta n \frac{L^2}{t_1} \left( \frac{t_1}{t_2} + \frac{t_1^2}{t_2^2} \right) \left( 1 + \frac{t_1}{t_2} \right)^2 + \left( \frac{E_2 t_2}{E_1 t_1} + \frac{t_1^3}{t_2^3} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-1}$$

(15)

is the deflection caused by electronic stress. Note that equation (14) is equivalent to equations given by a number of literatures [1-3], while equation (15) is somewhat different from the literature report [4-6].

For micromechanical photon detectors, we mainly care about the deflection caused by electronic stress since it is several times larger than the deflection caused by thermal stress [4, 6]. However, in
order to eliminate the cancel effect of thermal stress, it is better to choose material combination that both \( \frac{d\varepsilon_g}{dP} \) and \( \frac{2\varepsilon_d}{\varepsilon_{cm}} \) take the same polarity.

To achieve high sensitivity micromechanical photon detector, i.e. to obtain large deflection of the semiconductor-bilayer cantilever under the same radiant power, the material combination and the cantilever parameters must be optimized.

From equation (15) we can obtain the sensitivity of the micromechanical photon detector:

\[
S = \frac{\delta E}{\Phi_{E}^{obs}} = C_0 \tau_L \frac{d\varepsilon_g}{dP} \left( 1 - \frac{\lambda}{\lambda_c} \right) \frac{L}{wt_1^2} \left( t_1 + \frac{t_1^2}{t_2} \right) \left( 1 + \frac{t_1}{t_2} \right)^2 + \left( \frac{E_2 t_2 + t_2^2}{E_1 t_1 + t_1^2} \right) \left( 1 + \frac{E_1 t_1}{E_2 t_2} \right)^{-1}
\]

(16)

For best understanding, equation (16) can be rewritten as

\[
S = S_1(C_0, \tau_L, d\varepsilon_g / dP, \lambda_c, \lambda, L, w, t_1) \cdot S_2(r_1, r_2)
\]

(17)

in which,

\[
S_1(C_0, \tau_L, d\varepsilon_g / dP, \lambda_c, \lambda, L, w, t_1) = C_0 \tau_L \frac{d\varepsilon_g}{dP} \left( 1 - \frac{\lambda}{\lambda_c} \right) \frac{L}{wt_1^2}
\]

(18)

\[
S_2(r_1, r_2) = \left( r_1 + r_2^2 \right) \left( 1 + r_1 \right)^2 + \left( \frac{1}{r_1 r_2} + r_1^2 \right) \left( 1 + r_1 r_2 \right)^{-1}
\]

(19)

Here \( r_1 = t_1 / t_2 \) is the thickness ratio and \( r_2 = E_1 / E_2 \) is the modulus ratio.

It is obvious that the first term \( S_1(C_0, \tau_L, d\varepsilon_g / dP, \lambda_c, \lambda, L, w, t_1) \) of the sensitivity depends on the property and geometry of the semiconductor, while the second term \( S_2(r_1, r_2) \) depends on the thickness ratio and modulus ratio of the bilayer. Therefore, the optimization of the first term gives proper material choice and geometry of the semiconductor layer, while the second term gives the material choice and geometry of the bilayer.

### 4.2. Semiconductor material choice and geometry determination

For high sensitivity, the semiconductor material should be chosen to obtain the largest electronic stress, i.e. \( d\varepsilon_g / dP, \tau_L \) and \( \lambda_c \) should be large. From table 1 \[6\] we can see that InSb is superior to other semiconductor materials for micromechanical photon detectors, especially infrared detectors. However, silicon is the most widely used semiconductor material and has advantages of low cost, high quality and processing friendliness.

| Semiconductor material | \( \varepsilon_g \) (eV) | \( d\varepsilon_g / dP \) \( \times 10^{26} \) cm\(^3\) | \( E \) (Gpa) | \( G \) (Wm\(^{-1}\)K\(^{-1}\)) |
|------------------------|----------------|----------------------|------|-----------|
| GaAs                   | 1.35           | -13.67               | 85.5 | 55        |
| Si                     | 1.12           | -3.14                | 130.91 | 163      |
| Ge                     | 0.67           | 11.52                | 102.66 | 59       |
| InSb                   | 0.16           | 23.61                | 42.79 | 36        |

Based on equation (18), long length, short width and small thickness of semiconductor layer give rise to sensitivity, and thickness is the most sensitive parameter. However, present micromachining technology limits the length and thickness of semiconductor cantilever. For silicon material, with the state-of-the-art technology, 100\( \mu \)m long, 20\( \mu \)m wide and 0.5\( \mu \)m thick cantilevers are commercially available.

### 4.3. Bilayer material choice and geometry determination
After the determination of the semiconductor material and geometry, corresponding bilayer material and geometry can be determined by only considering its relative modulus and thickness.

Optimized thickness ratio and modulus ratio can be derived from equation (19). Figure 2 described the relationship between the sensitivity $S_2(r_1, r_2)$ and the thickness ratio $r_1$ and modulus ratio $r_2$. It is obvious that lower modulus ratio gives a higher sensitivity, i.e. the modulus of the bilayer material should be as large as possible. However, when the modulus ratio is set, the thickness ratio has an optimized value. It is even clearer in figure 3 which shows three sensitivity curves with modulus ratio of 0.5, 1 and 2 respectively. Note that, the corresponding optimized thickness ratios are 2.8, 2.0 and 1.5 respectively.

![Figure 2. 2-D plot of $S_2(r_1, r_2)$](image)

![Figure 3. Sensitivity curves with different modulus ratio](image)

### 4.4. Design of high sensitivity silicon-based micromechanical photon detectors

Since silicon is a widely used semiconductor material and has mature processing technology, here consider an optimized design of silicon-based micromechanical photon detector.

![Figure 4. Sensitivity curve of Si/Si$_3$N$_4$ cantilever](image)

![Figure 5. Sensitivity curve of Si/Al cantilever](image)

If a commercially available silicon cantilever with dimension of 100$\mu$m in length, 20$\mu$m in width and 0.5$\mu$m in thickness is chosen, then $E_1 = 1.0 \times 10^{11} \text{ N/m}^2$ and $t_1 = 0.5\mu\text{m}$ is set. Since larger relative modulus is preferred for high sensitivity, Si$_3$N$_4$ ($E = 3.0 \times 10^{11} \text{ N/m}^2$) or SiC...
(\(E = 4.0 \times 10^{11} \text{ N/m}^2\)) can be chosen as the bilayer material [8]. Taking \(E_2 = 3.0 \times 10^{11} \text{ N/m}^2\) as the bilayer modulus, then the sensitivity varies with the thickness ratio is illustrated in figure 4. The optimized thickness ratio \(n\) is 3.35, and the corresponding sensitivity \(S_2(n_1, n_2)\) is 1.77.

As a compare, the sensitivity of the same silicon cantilever with a 30nm Al coating as the bilayer is also calculated as shown in figure 5. The modulus of Al is \(E = 0.7 \times 10^{11} \text{ N/m}^2\), so the modulus ratio is 10/7 and the thickness ratio is 16.7. Note that the sensitivity for this case is 0.038, about 47 times lower than optimized design.

After the calculation, the only problem left is that if silicon and Si\(_3\)N\(_4\) are chosen as the material combination, it is not possible to form Shottcky junction, so that the cut-off wavelength will be short (in visible light range). Nevertheless, this problem can be solved by coating an ultra-thin metal layer such as Pt onto the silicon surface. As previous calculation has shown, the sensitivity will not be significantly affected if the metal layer takes a thickness less than 30nm. The structure of this kind of silicon-based micromechanical photon detector is shown in Figure 6.

![Figure 6. Structure of a high sensitivity silicon-based micromechanical photon detector](image)

5. Conclusions

The theory of bilayer cantilevers with different stress in each layer is deducted and is applied to the design of micromechanical photon detectors. This theory is somewhat different from the theory in many literatures because it is based on not surface stress but layer stress. With this theory, optimized design of micromechanical photon detectors can be performed, which includes both material choice and geometry determination. As an example, a high sensitivity silicon-based micromechanical photon detector is designed, which reaches a sensitivity of 47 times larger than conventional designs.

Acknowledgments

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