IMPACT OF SILICON NITRIDE THICKNESS ON THE INFRARED SENSITIVITY OF SILICON NITRIDE-ALUMINUM MICROCANTILEVERS

BY

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THESIS

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ABSTRACT

This thesis investigates how silicon nitride thickness impacts the performance of silicon nitride-aluminum bimaterial cantilever infrared sensors. A model predicts cantilever behavior by considering heat transfer within and from the cantilever, cantilever optical properties, cantilever bending mechanics, and thermomechanical noise. Silicon nitride-aluminum bimaterial cantilevers of different thicknesses were designed and fabricated. Cantilever sensitivity and noise were measured when exposed to infrared laser radiation. For cantilever thickness up to 1200 nm, thicker silicon nitride results in improved signal to noise ratio due to increased absorptivity and decreased noise. The best cantilever had an incident flux sensitivity of $2.1 \times 10^{-3}$ V W$^{-1}$ m$^2$ and an incident flux signal to noise ratio of 406 Hz$^{1/2}$ W$^{-1}$ m$^2$, which is more than an order of magnitude improvement compared to the best commercial cantilever.
This thesis is dedicated to my Lord and Savior, Jesus Christ, and to my parents for their unending support and encouragement.
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CHAPTER 1: INTRODUCTION

Bimaterial cantilevers are sensitive thermometers with resolutions in the range of 2 µK [1] and 100 pW [2]. Bimaterial cantilevers are effective temperature sensors at room temperature because their noise characteristics are not a strong function of temperature [3]. As a result, many researchers have explored uncooled infrared (IR) imaging with bimaterial cantilevers [4-6].

Published research reports modeling and design of biomaterial cantilevers that has resulted in substantial performance improvements. Aluminum - silicon nitride is a better material combination than gold - silicon nitride because aluminum has a higher thermal expansion coefficient and a similar Young’s modulus compared to gold [1]. When heat is absorbed at the cantilever free end, the optimal thickness ratio of an aluminum - silicon nitride cantilever is 0.26 [1]. An aluminum – silicon nitride cantilever with a thickness ratio of 0.25 had a measured heat flow resolution of 40 pW when uniformly illuminated by incident light [3]. When a gold - silicon nitride cantilever is heated to a uniform temperature, the thickness ratio to maximize sensitivity is 0.75 [4]. Increasing the thermal isolation of the absorbing area can enhance cantilever sensitivity [4, 7]. Despite intense research in this general area, the effect of total cantilever thickness [4] and optical properties [8] has been somewhat less studied.

In a metal-dielectric cantilever, the metal layer reflects incident light while the dielectric layer absorbs incident light. The thickness of both layers affect cantilever temperature sensitivity and noise, while the thickness of the dielectric layer affects cantilever absorption. Silicon nitride is a common choice for the absorbing dielectric layer because it has relatively high absorption across the relevant IR wavelength range of 8-14 µm [4]. The refractive index of silicon nitride has a large imaginary part in this IR range [9] that results in a strong dependence of absorptivity
on layer thickness up to 1.5 µm, with absorptivity increasing with thickness. Cantilever noise decreases with thickness because the cantilever becomes more rigid as thickness increases. However, cantilever temperature sensitivity, which is independent of absorptivity, decreases with increasing thickness [1, 4]. Previous publications have not considered this tradeoff between cantilever absorptivity, noise, and temperature sensitivity. This work uses modeling and experiments to investigate how silicon nitride thickness affects the performance of silicon nitride–aluminum bimaterial cantilevers.
CHAPTER 2: MODELING

The objective of the model is to predict the sensitivity and signal to noise ratio (S/N) of bimaterial cantilevers to IR radiation. Figure 2.1a shows the bimaterial cantilever geometry and its dimensions. Changing any dimension of the cantilever affects the behavior, but the model will show that varying the absorbing layer thickness (layer 2) is of particular interest. Figure 2.1b shows a scanning electron microscope image of a bimaterial cantilever fabricated for this study.

Figure 2.1 a) Schematic of bimaterial cantilever geometry labeling length, \( L \), width, \( w \), layer 1 thickness, \( t_1 \), and layer 2 thickness, \( t_2 \). b) Scanning electron microscope image of a bimaterial cantilever fabricated for this study.
Bimaterial cantilever thermal bending can be modeled as a bimaterial strip thermostat [10]. Equating the strain in the two materials at their interface gives the cantilever bending as

$$\frac{d^2 z(x)}{dx^2} = 6(\alpha_1 - \alpha_2) \left( \frac{t_1 + t_2}{t_2 K} \right) [T(x) - T_0]$$

(1)

where

$$K = 4 + 6r + 4r^2 + \frac{E_1}{E_2} r^3 + \frac{E_2}{E_1} r,$$

(2)

$z(x)$ is the cantilever deflection along its length, $\alpha$ is the thermal expansion coefficient, $t$ is the layer thickness, $T(x)$-$T_0$ is the temperature difference between the cantilever and the environment temperature, $r = t_1/t_2$, $E$ is the Young’s modulus, and the subscripts refer to the two materials. The boundary conditions for Eq. (1) are $dz/dx = 0$ and $z = 0$ at $x = 0$.

The temperature distribution within the cantilever can be considered one-dimensional, since the Biot number for a cantilever is less than $10^{-3}$ [11]. Heat flow from the cantilever to the nearby environment can be modeled using a constant convection heat transfer coefficient, $h = 1000$ W/m$^2$-K [12-15]. The incident radiation flux on the cantilever, $q_{rad}$, is uniform over the entire cantilever. With these considerations, the steady state temperature distribution in the cantilever is

$$\theta(x) = C_1 (\cosh(\beta x) - 1) + C_2 \sinh(\beta x)$$

(3)

$$\beta = \sqrt{\frac{hP}{w(\lambda t_1 + \lambda_2 t_2)}}$$

(4)

$$C_1 = -\frac{\lambda q_{rad} w}{hP}$$

(5)
\[ C_2 = \frac{A q_{rad} w}{hP} \frac{\frac{\lambda}{h} \beta \sinh(\beta L) + \cosh(\beta L) - 1}{\sinh(\beta L) + \frac{\lambda}{h} \beta \cosh(\beta L)} \]  

where \( \theta(x) = T(x) - T_0 \), \( A \) is cantilever absorptivity, \( P \) is the perimeter of the cantilever cross section, and \( \lambda \) is the thermal conductivity. The steady state temperature distribution is considered because it corresponds to the largest deflection. The boundary conditions are \( \theta(0) = 0 \) and 
\[
\frac{d\theta}{dx} \bigg|_{x=L} = \frac{h}{\lambda} \theta'(L).
\]

Cantilever tip slope determines the difference signal measured by the position sensitive detector (PSD) in an atomic force microscope (AFM) [16]. Combining Eqs. (1) and (3), the cantilever slope at the free end is 
\[
\frac{dz}{dx} \bigg|_{x=L} = 6(\alpha_1 - \alpha_2) \left( \frac{t_1 + t_2}{t_2^2 K} \right) \left[ C_1 \frac{\sinh(\beta L)}{\beta} - C_2 x + C_2 \frac{\cosh(\beta L)}{\beta} + C_3 \right]
\]  

where \( C_3 = -C_2 / \beta \). To compare modeling with experiments, we relate cantilever tip slope with the PSD difference signal through the inverse optical lever sensitivity (InvOLS). The InvOLS is the ratio of tip deflection to the PSD difference signal when the cantilever tip is in contact with a surface. For this loading condition, the ratio of tip deflection to tip slope is \( 2L/3 \) [17]. Therefore, the factor relating PSD difference signal to cantilever tip slope is \( 3/(2L) \cdot \text{InvOLS} \).

Cantilever absorptivity is calculated with the transfer matrix method and depends on the thickness and refractive index of the cantilever materials [18]. The modeling is specifically for the experimental laser wavelength, 10.35 \( \mu m \), but similar trends exist for different wavelengths.

Reflectivity measurements and optical modeling show that the refractive index of our plasma enhanced chemical vapor deposition (PECVD) silicon nitride films is \((1.24 \pm 0.05) + i (1.15 \pm 0.15)\) at a wavelength of 10.35 \( \mu m \). The measured refractive index of our silicon nitride films is
similar to that found in previous studies of PECVD silicon nitride [9]. Commercial AFM cantilevers contain low-pressure chemical vapor deposition silicon nitride which has a refractive index of $1.28 + i1.88$ at 10.35 $\mu$m [19].

Figure 2.2a shows predictions for absorptivity, absorbed flux sensitivity (independent of absorptivity), and incident flux sensitivity as functions of silicon nitride thickness for constant $r$, $L = 450 \mu$m, and $w = 40 \mu$m. The incident flux sensitivity is the product of absorbed flux sensitivity and absorptivity. Absorptivity changes significantly in the 400-1500 nm silicon nitride thickness range. As cantilever thickness increases, the absorbed flux sensitivity monotonically decreases. However, the incident flux sensitivity has a local maximum because the steep positive slope of absorptivity overwhelms the negative slope of absorbed flux sensitivity until around 1200 nm.

S/N determines the detection resolution of bimaterial cantilever sensors. There are many sources of noise in cantilever sensors including temperature fluctuation noise, optical readout noise, and thermomechanical noise [7]. Thermomechanical noise [4] is a dominant noise source for cantilevers with an optical system for deflection measurement [20]. The frequency distribution of noise is relevant because heat inputs to bimaterial cantilevers are often modulated at a specific drive frequency [1, 3, 7, 15, 21, 22]. At frequencies well below mechanical resonance, the root mean square amplitude of cantilever tip deflections from thermomechanical noise is [23]:

$$\langle \delta z_{TM}^2 \rangle^{1/2} = \sqrt{\frac{4k_B T B}{Q k \omega_0}}$$

(8)

where $k_B$ is the Boltzmann constant, $B$ is the measurement bandwidth, $Q$ is the quality factor, $k$ is the mechanical spring constant, and $\omega_0$ is the mechanical resonance frequency. The tip slope noise is the product of Eq. (8) and the ratio of tip slope to tip deflection for the first vibrational
bending mode, $1.3765/L$ [20]. Slope is converted to signal through the InvOLS as described for the cantilever response to radiation. While thermomechanical noise decreases with increased stiffness, the noise floor is governed by the AFM, which in our case was $5 \times 10^{-6} \text{ V Hz}^{1/2}$. Figure 2.2b shows the qualitative behavior of thermomechanical noise and incident flux S/N with respect to silicon nitride thickness. The model predicts that an increase in silicon nitride layer thickness corresponds to an increase in S/N.
Figure 2.2 a) Predictions for absorbed flux sensitivity, incident flux sensitivity, and absorptivity versus SiN$_x$ thickness. Absorbed flux sensitivity and incident flux sensitivity are normalized by the absorbed flux sensitivity at 400 nm. b) Predictions for incident flux S/N and thermomechanical noise versus SiN$_x$ thickness. Incident flux S/N is normalized by S/N at 1500 nm and thermomechanical noise is normalized by thermomechanical noise at 400 nm.
CHAPTER 3: CANTILEVER FABRICATION AND CHARACTERIZATION

Figure 3.1 shows the fabrication process for our bimaterial cantilevers. The fabrication process began with a 400 \( \mu \)m thick double side polished silicon wafer. First, an aluminum layer was sputtered or evaporated onto the silicon surface. PECVD silicon nitride was then deposited on top of the aluminum. To compensate for compressive thermal stress, the silicon nitride film was deposited at high frequency which generally leads to tensile stress [24]. PECVD silicon nitride films are not necessarily stoichiometric and so here we refer to the silicon nitride as Si\(_x\) [9]. The films were annealed at 375 °C to improve adhesion between Si\(_x\) and aluminum and to mitigate intrinsic stresses. The Si\(_x\) layer was patterned and plasma etched, and then the aluminum layer was wet etched. Finally, the cantilevers were released with deep reactive ion etching from the wafer back side. Annealing between 175 °C and 185 °C caused initially bent cantilevers to become flat enough for use in an AFM. Figure 2.1b shows a released cantilever. Table 3.1 shows the measured dimensions of all fabricated cantilevers as well as several commercial cantilevers that were studied.
Figure 3.1 Outline of fabrication process.  a) Double-side polished silicon wafer with sputtered aluminum and PECVD silicon nitride. b) Silicon nitride patterned via RIE with CF$_4$ and aluminum patterned via wet etchant. c) Backside through-etch with ICP-DRIE.

<table>
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<th>Cantilever Name</th>
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<th>Width [µm]</th>
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<tr>
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<td>63</td>
<td>400</td>
<td>55 (Au)</td>
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Table 3.1 Cantilever type, shape, and dimensions. A-G are cantilevers fabricated for this work while α, β, and γ are commercial cantilevers.
The goal of the characterization was to measure cantilever bending sensitivity and S/N when exposed to IR radiation. Figure 3.2 shows the experimental setup. A cantilever was mounted in an AFM and the optical readout system in the AFM head measured the deflection. A CO$_2$ laser tuned to 10.35 µm illuminated the cantilever. The beam diameter from the laser was 2.4 mm. A 1 mm diameter aperture was positioned between the laser and the cantilever, and the flux through the aperture was assumed constant because the beam diameter was considerably larger than the aperture.

![Diagram of experimental setup.](image)

**Figure 3.2** Diagram of experimental setup. The Gaussian beam from the CO$_2$ laser is restricted by an aperture to create approximately uniform incident light at the cantilever. The AFM PSD senses deflection of the cantilever that is mounted in the AFM head.

Figure 3.3a shows the raw PSD signal as a function of time. Measuring the time domain signal was advantageous because it ensured that the full cantilever deflection was measured. Turning the laser on and off led to rapid changes in the cantilever deflection signal. There was
some drift in the signal over time, but the drift was so slow that it had a negligible effect on the cantilever response to the laser, which was very fast (<15 msec). Neutral density IR filters attenuated the CO$_2$ laser power which enabled the measurement of different magnitudes of incident flux. Figure 3.3b shows several data points, each corresponding to a change in deflection as shown in Figure 3.3a. The incident flux was found by measuring the power through the aperture and dividing by aperture area. Figure 3.3b verifies the linear relationship between cantilever bending and incident flux, which the model predicted.

Figure 3.3c shows the cantilever noise in the frequency domain including a thermal fit from the AFM software. The experimental value for noise was taken as the point where the noise curve flattens out below $\omega_0$. For many cantilevers, the noise increased at low frequencies, possibly due to environmental noise sources or 1/f noise, but we are interested in the fundamental thermomechanical noise limit [4]. Bimaterial cantilevers can operate at a sufficiently high frequency that the noise level is flat, but the bending response is still maximized [15].
Several figures of merit were calculated from the measurements. Incident flux sensitivity is the change in PSD difference signal per unit incident laser flux. Absorbed flux sensitivity is the incident flux sensitivity divided by the calculated absorptivity. Power sensitivity is flux sensitivity divided by cantilever area. Experimental S/N is the sensitivity in units of $V \text{ W}^{-1} \text{ m}^2$ divided by the measured noise density in units of $V \text{ Hz}^{-1/2}$. Combining the steady sensitivity
measurement with the frequency domain noise measurement is relevant because in frequency
modulated bimaterial cantilever applications, the frequency can be low enough that the cantilever
reaches its steady deflection during each cycle [15].
CHAPTER 4: RESULTS AND DISCUSSION

Figure 4.1 shows measurements and predictions for incident flux sensitivity and S/N versus SiNx thickness for several thickness ratios. The maximum predicted sensitivity is for a SiNx thickness between 1100 - 1200 nm, depending on thickness ratio (Fig. 4.1a). Figure 4.1b shows that S/N generally increases with increasing SiNx thickness, until S/N starts to decline when the noise is governed by the AFM noise floor. The incident flux sensitivity is not a strong function of SiNx thickness near the maximum point. For instance, with $r = 0.16$, increasing SiNx thickness from 750 nm to 1250 nm only increases the sensitivity by 24%. On the other hand, incident flux S/N increases by 242% over the same range. The substantial S/N enhancement over this range is primarily the result of decreased noise. Figure 4.1 also confirms the well-established concept that cantilever performance depends on $r$ [1, 4].
Figure 4.1 a) Comparison of model and experiment for incident flux sensitivity as a function of SiNx thickness. The thickness ratio \( r \) is the Al thickness divided by the SiNx thickness. b) Corresponding plot of S/N. The predictions are based on \( L=450 \, \mu m \), \( W=40 \, \mu m \), \( Q=10 \), and \( h=1000 \, \text{W m}^{-2} \text{K}^{-1} \). Black squares \((r=0.05)\), red triangles pointing up \((r=0.16)\), blue triangle pointing down \((r=0.24)\), and magenta diamonds \((r=0.37)\) are experimental data points.

Figure 4.2 summarizes the data for all cantilevers tested. Figure 4.2a shows the incident power sensitivity and the corresponding S/N. Figure 4.2b shows the incident flux sensitivity and S/N. Cantilevers B (1050 nm SiNx, \( r=0.17 \)) and C (650 nm SiNx, \( r=0.15 \)) have approximately
the same incident power and flux sensitivities, but B has significantly higher S/N. Larger SiN$_x$ thickness increases absorptivity and also decreases thermomechanical noise, which leads to higher S/N.

**Figure 4.2** Measured cantilever performance for all cantilevers tested in this work. a) Incident power sensitivity (black squares) and S/N (red triangles). b) Incident flux sensitivity (black squares) and S/N (red triangles).
A few commercially available AFM cantilevers were measured for comparison. Cantilever \( \beta \) was chosen because it was predicted to have the best performance among the commercial cantilevers we found [15]. Cantilever A achieves a 12X improvement for incident flux sensitivity and a 21X improvement in S/N compared to cantilever \( \beta \). The main reasons for this improvement are that A has a thicker absorbing layer, a better material combination (SiN/Al compared to SiN/Au), and more absorbing area. Cantilever A also outperforms cantilever \( \beta \) by 6X for incident power S/N.

Table 4.1 presents the incident and absorbed flux sensitivity and S/N for typical cantilevers of each type. Cantilever C (650 nm SiN\(_x\), \( r=0.15 \)) has 2X the absorbed flux sensitivity of cantilever B (1050 nm SiN\(_x\), \( r=0.17 \)), but cantilever B has 3X the absorbed flux S/N of cantilever C. The absorbed flux sensitivity and S/N are independent of cantilever absorptivity, so the high absorptivity of cantilever B does not improve its absorbed flux performance compared to cantilever C. However, the reduced noise in cantilever B was more than sufficient to overcome the sensitivity reduction compared to cantilever C.

| Cantilever | Incident Flux | | | Absorbed Flux | | | Absorptivity |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
|           | Sensitivity | Signal to Noise | Absorptivity | Sensitivity | Signal to Noise | Absorptivity |
|           | Predicted | Measured | Predicted | Measured | Predicted | Calculated | Predicted | Calculated | Calculated |
| A         | 21.4       | 20.6       | 42.8       | 40.6       | 31.0       | 29.9       | 62.1       | 58.8       | 0.69       |
| B         | 12.6       | 14.8       | 25.2       | 19.8       | 26.2       | 30.8       | 52.5       | 41.3       | 0.48       |
| C         | 13.1       | 14.4       | 4.1        | 3.1        | 63.3       | 69.4       | 19.6       | 14.7       | 0.21       |
| D         | 21.1       | 22.1       | 20.0       | 13.8       | 52.3       | 54.7       | 49.6       | 34.1       | 0.40       |
| E         | 5.6        | 8.1        | 4.8        | 5.2        | 16.5       | 23.6       | 14.2       | 15.2       | 0.34       |
| F         | 12.1       | 14.9       | 3.4        | 8.1        | 34.3       | 42.1       | 9.6        | 22.9       | 0.35       |
| G         | 6.2        | 9.0        | 2.0        | 5.8        | 17.4       | 25.3       | 5.5        | 16.3       | 0.36       |
| a         | 0.1        | 0.2        | 0.9        | 0.5        | 2.0        | 4.5        | 18.5       | 9.9        | 0.05       |
| \( \beta \) | 1.8        | 1.7        | 2.0        | 1.9        | 9.4        | 8.9        | 10.3       | 10.0       | 0.19       |
| y         | 1.4        | 0.3        | 1.9        | 0.3        | 13.7       | 3.0        | 18.1       | 2.8        | 0.10       |

Table 4.1 Summary of sensitivity and S/N for incident and absorbed flux.
One application in which flux sensitivity is relevant is photothermal spectroscopy because the cantilever area is smaller than the light source. Van Neste et al. measured absorption spectra of explosive residues using bimaterial cantilever based photothermal spectroscopy [21]. Cantilever A has ~4X better incident flux sensitivity and S/N than the cantilever used in Ref. [21].

Power sensitivity and minimum detectable power (inverse of S/N) are figures of merit often used to compare bimaterial cantilevers. Varesi et al. reported a minimum detectable absorbed power of 40 pW at a measurement bandwidth of 26 mHz [3]. Cantilever A has a minimum detectable power of 4 pW for a measurement bandwidth of 26 mHz. Thus, cantilever A has about 10X improved minimum detectable power compared to Ref. [3].

Detectivity, \( D^* \), is another figure of merit for radiation sensors and is defined as

\[
D^* = \sqrt{\frac{A_{\text{cant}}}{N}}
\]

where \( A_{\text{cant}} \) is the cantilever area and \( N \) is the noise-spectral density [3]. Varesi et al. demonstrated \( D^* \) of \( 4.6 \times 10^7 \) cm Hz\(^{1/2} \) W\(^{-1} \). In comparison, cantilever A has \( D^* \) of \( 4.8 \times 10^8 \) cm Hz\(^{1/2} \) W\(^{-1} \), an improvement of about one order of magnitude.

Overall, the modeling and experiments show that the best bimaterial cantilever is not the thinnest and most sensitive cantilever, but rather the cantilever that has the best combination of sensitivity, noise, and absorptivity. Increasing the SiN\(_x\) thickness improves infrared radiation sensing performance by decreasing thermomechanical noise and increasing absorptivity. In practice, the deflection measurement scheme will set the noise floor. Increasing SiN\(_x\) thickness to reduce thermomechanical noise below this noise floor will not decrease the overall measurement noise and will eventually decrease S/N. The optimal SiN\(_x\) thickness is a function of thickness ratio, length, and width because these parameters also affect thermomechanical
noise and sensitivity. Figure 4.1b illustrates the change in optimal SiN$_x$ thickness for different thickness ratios. As a result, the absolute values for optimal SiN$_x$ thickness presented here should not be viewed as rigid design rules, but rather serve as a design guide.
CHAPTER 5: CONCLUSION

Optimization of silicon nitride thickness in silicon nitride-aluminum biomaterial cantilevers leads to significant improvements in cantilever radiation sensing performance. Increased silicon nitride thickness causes decreased thermomechanical noise and increased absorptivity. The optimal silicon nitride thickness is a function of deflection measurement scheme, cantilever length, cantilever width, and cantilever thickness ratio, so the optimal silicon nitride thickness will vary depending on the application. Compared to the best commercial cantilevers, cantilevers fabricated with \( L=450 \, \mu m, \ W=40 \, \mu m, \ r=0.37, \) and 1400 nm thick silicon nitride achieved a 21X improvement in incident flux S/N and a 6X improvement in incident power S/N.
REFERENCES


