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# FEM Analysis for the Influence of manufacturing process Defects on Dynamic Behavior of Thin Chromium Microbeam

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**Abstract.** This paper identifies and investigates the influence of technological defects of manufacturing process on the dynamic behavior of thin chromium microbeam. The analytical models will be analyzed and corrected using finite element method (FEM) to determine their validity under influence of technological defects. A semi-analytical model will be proposed for the extraction of corrective factors from 3D FEM simulation of dynamic behavior of microbeam. Final results indicate that the correction of technological defects is very significant for Cr microbeam  $80 \times 2 \times 0.95 \mu\text{m}^3$ . In other hand, the corrected value of Young's modulus is very close to the experimental results and it is about 279.1GPa.

## Introduction

Microbeam is relatively a new approach allows the possibility to miniaturize sensors and actuators through the integration of electrical and mechanical functions in the single chip [1,2]. However, dynamic behavior is very sensitive to the technological defects such as underetching at the clamped-end and nonrectangular cross-section due to the manufacturing process [3-5]. Several methods have been already proposed for the study of dynamic behavior to extract thin films mechanical proprieties as way of example, the Young's modulus [6-8]. For rigid materials like chromium it is often more appropriate to measure the variations of resonance frequency of microdevice for accurate determination of Young's modulus value.

## Ideal Beam Model of Natural Frequencies

The classical beam model describes the mechanical behavior of a clamped-free microbeam without the rotation of rectangular cross-section  $A$ . When  $L(A/I)^{1/2} > 10^2$ , the effect of rotation will be important on the value of resonance frequencies [6,9]. Where  $L$  is the length of microbeam and  $I$  is the inertia moment. The Rayleigh Beam model (RBM) investigate the effect of rotation on the mechanical behavior of a microbeam [9]. The resonant frequencies are given by the following expression:

$$f_n^r = \frac{\sqrt{a_n^{r^2} - b_n^{r^2}}}{2\pi L} \sqrt{\frac{Y}{\rho}} \quad (1)$$

Where,  $Y$  and  $\rho$  are respectively the effective Young's modulus and the density of the beam material. The coefficients  $a_n^r$  and  $b_n^r$  are calculated numerically under MATLAB software using Eqs. 2 and 3.

$$\sqrt{12 \left( a_n^{r^2} - b_n^{r^2} \right)} = H a_n^r b_n^r \quad (2)$$

$$\left(a_n^{r^2} - b_n^{r^2}\right) a_n^r b_n^r \sin a_n^r \sinh b_n^r - \left(a_n^{r^4} + b_n^{r^4}\right) \cos a_n^r \cosh b_n^r = 2 \left(a_n^r b_n^r\right)^2 \quad (3)$$

### Technological defects of manufacturing process

Real microbeam has several differences from ideal microbeam; it has generally an underetching at the clamped-end (Figure 1 right). The underetching can be modeled by considering an elastic coupling with the substrate. This is equivalent to determination of the length  $L'$  of a microbeam produces the same effect as real microbeam of length  $L$  with an underetching  $L_{ue}$ . The corrective factor  $\gamma$  that allows introducing this effect is defined from the following equation:

$$L' = L(1 + \gamma) \quad (4)$$

In another hand, the geometry is defined by isotropic or quasi-isotropic etching the flanks of microbeam are arcs of circles (Figure 1 left). This effect can be quantified by introduction of a correction factor  $\beta$  in the resonance frequencies expressions. This corrective factor is defined as follows:

$$\beta = \left[ \frac{(I/A)}{(I/A)_{rect}} \right] - 1 \quad (5)$$

Where  $(I/A)_{rect} = H^2/12$  is the value of ratio for the rectangular cross-section. The ratio  $I/A$  is given by the following formula:

$$\frac{I}{A} = \frac{H^2}{12} \left[ \frac{\left[ I + \frac{H}{B} \left( 12 - \frac{7\pi}{2} \right) + \left( \frac{H}{B} \right)^2 \left( \frac{44}{3} - 7\pi - \frac{7\pi^2}{2} \right) \right]}{\left[ I + \frac{H}{B} (4 - \pi) + \left( \frac{H}{B} \right)^2 \left( 2 - \frac{\pi}{2} \right)^2 \right]} \right] \quad (6)$$

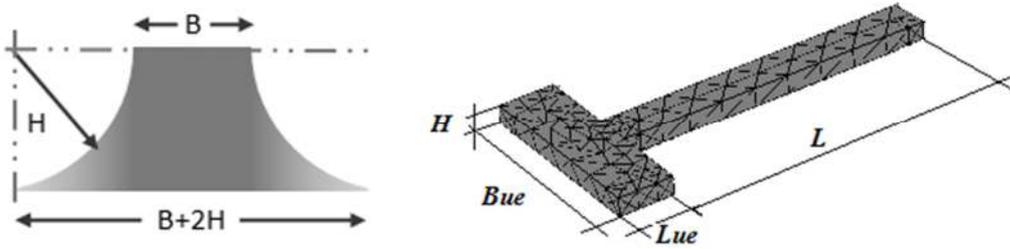


Fig. 1 Approximate non-rectangular cross-section shapes (left) and simulated microbeam with underetching at clamped-end (right).

### Numerical Correction with FEM Simulation

Numerical simulations have been implemented using parameterized programs developed under scripts to facilitate modifications in mechanical and geometrical parameters especially in the modeling of technological defects. The meshing parameters were optimized by study of the convergence of numerical computation. The frequencies expression given by the Eq. 1 shows that the resonant frequency is independent of the value of the width  $B$  and the Poisson's ratio  $\nu$  also. In fact, the Young's modulus  $Y$  varies with the ratio  $B/L$  (or  $B$ ) [3,4], we also consider that the Young's modulus could be written as:

$$Y = E \left( 1 + \alpha \frac{\nu^2}{1 - \nu^2} \right) \quad (7)$$

The FEM Analysis were performed to determine the variation of the correction factor  $\alpha$  and the Young's modulus  $Y$  is determined from resonant frequencies using Eq.1. The results show that the

difference noted between the corrective factor obtained for  $H=1\mu\text{m}$  by and the corrective factor obtained  $H=2\mu\text{m}$  is lower than 0.15% for both simulators (Figure 2 left). These curves confirm that the Young's modulus  $Y$  varies between the single axis Young's modulus  $E$  when  $B=0$  and the biaxial Young's modulus  $E/(1-\nu^2)$  when  $B/L=1$ . Therefore, the ratio width  $B/L$  is the significant magnitude for the correction of the effect of width  $B$ .

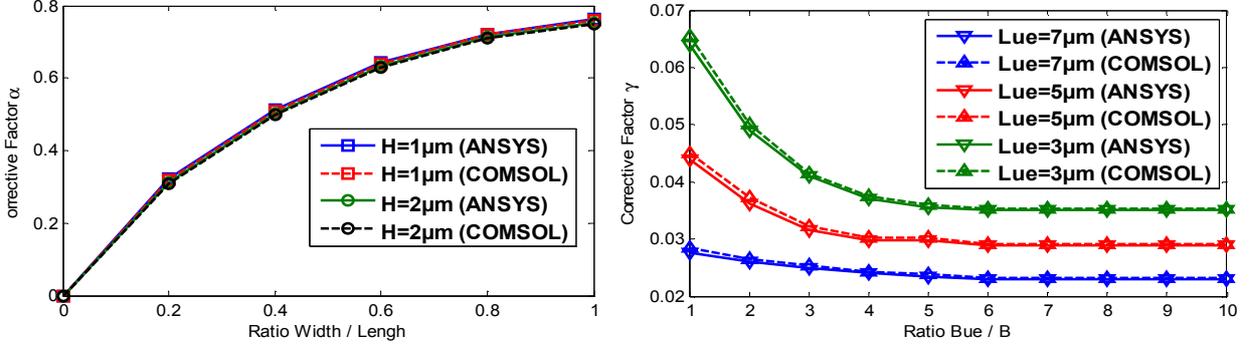


Fig. 2 The corrective factor  $\alpha$  as function of ratio  $B/L$  for various values of Height  $H$  (left), Variation of the corrective factor  $\gamma$  with the ratio  $B_{ue}/B$  for various values of underetching length  $L_{ue}$  (right).

Figure 2 (right) shows that the factor  $\gamma$  in logically converges to  $L_{ue}$  when the ratio  $B/L$  tends to 1 and becomes independent of the value of  $B/L$  when  $B_{ue}/B > 7$ . Therefore, the influence of the width  $B_{ue}$  on the areas stress concentration becomes low for higher values of  $B_{ue}$ . In summary, the resonant frequencies of a microbeam with nonrectangular cross-section shape and an underetching at the clamped-end can better be modeled by using the following equation:

$$f_n^{r*} = \frac{\sqrt{a_n^{r^2} - b_n^{r^2}}}{2\pi L (1 + \gamma)} \sqrt{\frac{E [1 + \alpha (\nu^2 / (1 - \nu^2)) (1 + \beta)]}{\rho}} \quad (8)$$

Where  $\alpha$ ,  $\beta$  and  $\gamma$  are correctives factors corresponding to the variation of the resonant frequency with width, cross-section shape and underetching at the clamped end of microbeam.

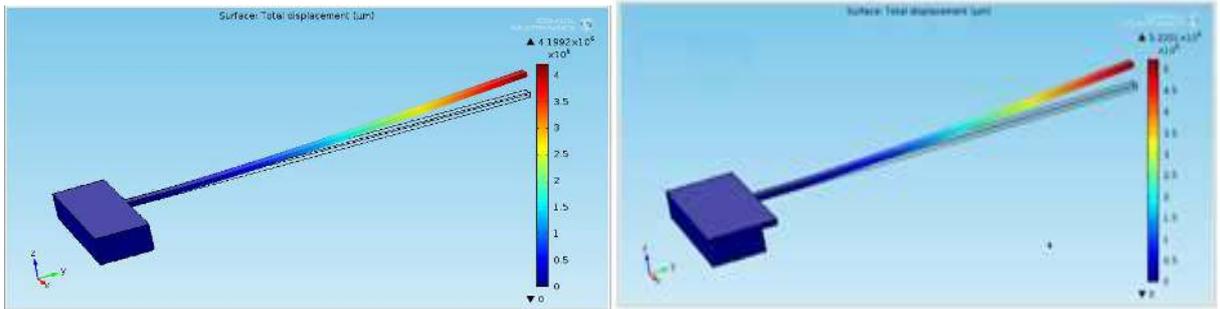


Fig. 3 First mode shape of microbeam ( $E=279 \text{ GPa}$ ,  $\nu=0.3$ ,  $\rho = 7190 \text{ Kg/m}^3$ ): without underetching (left); b) with underetching at the clamped-end (right).

### Influence of Defects on Young's Modulus

The values presented below correspond to a chromium microbeam with size  $80 \times 2 \times 0.95 \mu\text{m}^3$  (Figure 4 left). The microbeam is with nonrectangular cross-section, and having a length of underetching measured by SEM about  $3 \mu\text{m}$ . To extract a more precise value of the Young modulus  $Y$  from the frequencies of the first three modes shape we carried out modifications of the Eq. 8 to lead as:

$$\frac{4\pi^2 f_n^{r^2} \rho L^2 (1 + \gamma)^2}{1 + \alpha [\nu^2 / (1 - \nu^2)] (1 + \beta)} = Y (a_n^{r^2} - b_n^{r^2}) \quad (9)$$

Either by noting the left hand term of both equations  $Y_n$ , we obtain:

$$Y_n = Y \left( a_n^{r^2} - b_n^{r^2} \right) \quad (10)$$

The Young's modulus is thus the slope of the line given by the Eqs. 10.

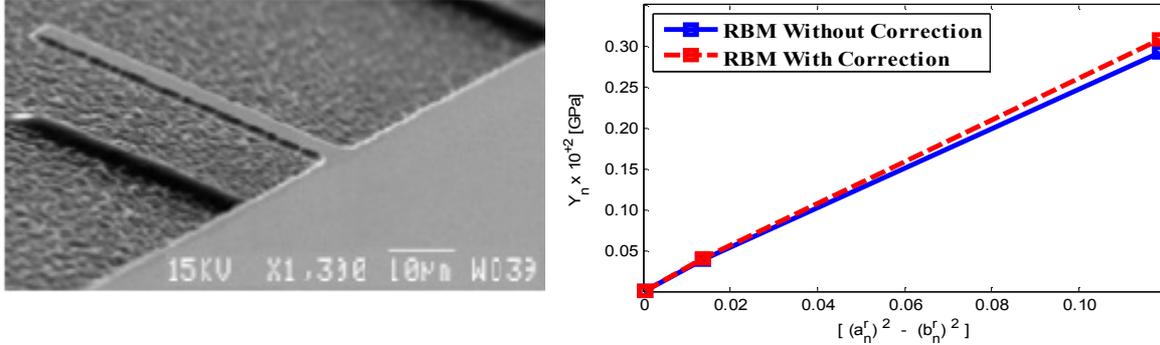


Fig. 4 SEM Image of Chromium Microbeam ( $\text{Cr } 80 \times 2 \times 0.95 \mu\text{m}^3$ ) (left) and Curve  $Y_n = f(a_n^{r^2} - b_n^{r^2})$  with and without correction.

As in the case of CBM model [3,4], correction gives also a huge impact and almost the same rate as in RBM model. However, for the RBM model, deduced value after correction (279.1GPa) is very close to the value of bulk chromium (279GPa) and the measured value by micro-vibrometry (281GPa) [3,4]. This may be due to the importance of rotation effect for thin chromium microbeam ( $L(A/I)^{1/2} > 10^2$ ). The results do not show only the importance of the influence of width and etching defect on value of Young's modulus but also the importance of the rotation of the cross-section for thin film layers.

Table 1 The first three values of Young's modulus calculated before correction from the measured frequencies.

Modes of vibration	$f$ measured [KHz]	Y [GPa] before correction	
		CBM [4]	RBM
1 <sup>st</sup> mode	0135.000	227.9022	264.6028
2 <sup>nd</sup> mode	0839.500	224.3974	277.3457
3 <sup>rd</sup> mode	2317.000	218.0236	245.7785

Table 2 Values of Young's modulus calculated after correction from the measured frequencies.

Analytical models	Y [GPa] before correction	Y [GPa] after correction	
		ANSYS	COMSOL
RBM	255.19065	279.05	279.076
CBM [4]	226.14980 [4]	250.3500 [4]	250.3487

## Conclusions

In this paper, semi-analytical approach has been presented for dynamic behavior analysis of thin microbeam. The results clearly show that analytical beam model can be used to study the effect of nonrectangular cross-section by considering a corrective factor  $\beta$  that could be calculated

analytically. The FEM analysis has been used to simulate dynamic behavior and the corrective factors have been successfully applied. The value of Young's modulus is very close to the experimental value for improved RBM model (279.1GPa). Therefore, this study allows the accurate determination of the Young's modulus value to properly investigate the dynamic behavior of microbeam where the revised RBM model is more suitable in order to investigate the effect of technological defects for thin microbeams.

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