Analysis and Design for a Micro-Mechanical Optical Switch

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Abstract: The mechanical and electric characteristics of a cantilever-beam micro-opto-mechanical switch are studied theoretically, with which the dependence of the flexion on the applied voltage is derived, as well as the formula of the threshold-voltage. The applied voltage, having no connection with the width of the beam, is in inverse proportion to the square of the beam's length. The deflection at the beam's tip cannot exceed 1/3 of the distance between two adjacent electrodes. These results are the basis of the switch design and development.

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1 Introduction

Micromechanical optical switches are developed greatly in recent years in the rapidly growing market of optical fiber networks and optical measurement instruments. The optical switches have many merits, such as low insertion loss, small crosstalk, large switching contrast, low manufacturing cost, etc. Much attention has been paid on the micromachining technology due to its potential ability to meet these requirements. Various types of micromechanical switches have been proposed[1-3] for the network application.

Owing to the increasing complexity of optical networks, it becomes more and more important to develop a fiber compatible optical switch, which is insensitive to the polarization and wavelength and has the advantage of network safety and reconfiguration. Micro-mechanical optical switch integrated on silicon is such an example. In recent years, optical waveguides on silicon (including SOI and SiO_2,) have developed rapidly[4-6] based on the integrated optics technology.

A cantilever-beam micro-opto-mechanical switch with SiO_2 optical waveguide on silicon has been designed and analyzed theoretically in this paper. By taking the mechanical and electric characteristics into consideration, the formula of the flexion versus the applied voltage for a cantilever-beam has been derived, with the threshold-voltage obtained. The deflection at the beam's tip can not exceed 1/3 of the distance between two adjacent electrodes. These results are the basis of the switch design and development.

2 Structure and Mechanism of the Device

The device's structure is shown in Fig. 1. The

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waveguide's structure, grown on silicon, is like a sandwich with 3 silica layers at different doping levels. Its mechanism is as follow: a cantilever beam bears the input waveguide. A voltage applied between two adjacent electrodes creates an electrostatic force, which makes the cantilever beam tip deflect from a distance. Consequently, the input waveguide will face the chosen output waveguide and can switch from one to the other.

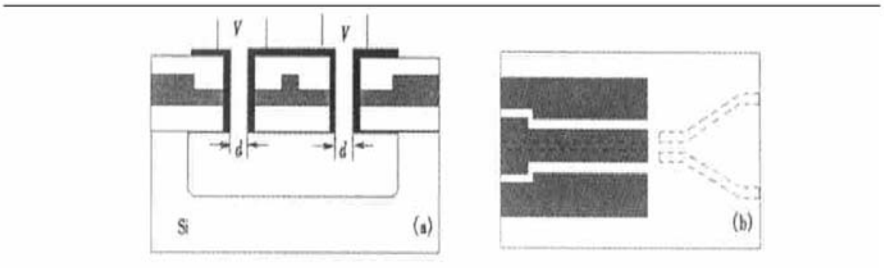

FIG. 1 Schematic View of Device (a) Cross-Section Drawing, (b) Vertical View

3 Basis of Mechanical-Electro Design

3.1 Dependence of Electrostatic Deflection of Cantilever Beam on Applied Voltage

The applied voltage is denoted as V. Since the cantilever beam is subjected to an electrostatic force, the beam tip is deflected, as shown in Fig. 2. According to the electromagnetic mechanism, the

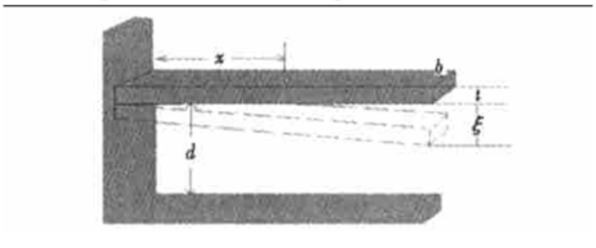

FIG. 2 Electrostatic Deflection of Cantilever Beam

bearing electrostatic force per unit area at the position x is

$$q(x) = \frac{\epsilon_0}{2}\left(\frac{V}{d - \delta(x)}\right)^2 \qquad (1)$$

where $\delta(x)$ is the deflection at the position x, approximately as

$$\delta(x) \approx \left(\frac{x}{l}\right)^2 \xi$$

where ξ is the total amount of electrostatic deflection at the beam tip under the applied voltage V. The electrostatic force at the position x on a uniform cantilever beam will cause a deflection at the tip of the beam, as is shown below[7].

$$\mathrm{d}\xi = \frac{x^2}{6EI}(3l - x)\,bq(x)\,\mathrm{d}x \qquad (2)$$

where E is Young's modulus, $I = \frac{1}{12}bt^3$ is the moment of inertia (t is the thickness), b is the width of the beam. Since the electrostatic force works at the whole beam, the total deflection at the tip of the beam is

$$\xi = \int_0^l \frac{x^2}{6EI}(3l - x)\,bq(x)\,\mathrm{d}x \qquad (3)$$

Substitute Eq. (1) into Eq. (3), we obtain:

$$\xi = \frac{b\epsilon_0 l^4 V^2}{12EId^2}\int_0^l \frac{(3l - x)x^2}{\left(l^2 - x^2\frac{\xi}{d}\right)^2}\mathrm{d}x \qquad (4)$$

Assuming $\Delta = \frac{\xi}{d}$, above equation can be simplified as

$$\Delta = \frac{b\epsilon_0 l^4 V^2}{12EId^3}\int_0^l \frac{(3l - x)x^2}{(l^2 - x^2\Delta)^2}\mathrm{d}x \qquad (5)$$

Consequently, the applied voltage V that is dependent on the electrostatic deflection (known as Δ) of the cantilever beam, is

$$V = \frac{(td)^{\frac{3}{2}}}{l^2}\left(\frac{2E}{3\epsilon_0}\right)^{\frac{1}{2}} \times \frac{\Delta}{\left(\frac{2}{3(1 - \Delta)} - \frac{\ln(1 - \Delta)}{3\Delta} - \frac{1}{2\sqrt{\Delta}}\ln\frac{1 + \sqrt{\Delta}}{1 - \sqrt{\Delta}}\right)^{\frac{1}{2}}} \qquad (6)$$

Discussion: the applied voltage V has no connection with the width of the beam, b, and is in inverse proportion to the square of the beam's length. These conclusions are the basis to determine the distance between two electrodes and the beam size.

3.2 Threshold Voltage

Equation (6) shows the relationship between applied voltage and the amount of deflection. However, there exists a maximum voltage, defined as threshold voltage, above which, the spring force and the electrostatic force on the beam can not be kept in equilibrium; in addition, there also exists a excess deflection at the tip of the beam, therefore a short circuit between two adjacent electrodes will take place.

At the tip of the beam, when equivalent spring constant is k_0. the net force will be

$$\sum F = \frac{1}{2}\epsilon_0\left(\frac{V}{d-\xi}\right)^2 bdx - k_0\xi = 0 \qquad (7)$$

In Eq. (7), supposing the derivative of the deflection (ξ) at the beam' tip is zero, then

$$\frac{1}{2}\epsilon_0 V^2 bdx\,\frac{2}{(d-\xi)^3} - k_0 = 0 \qquad (8)$$

Substitute Eq. (7) into Eq. (8), then Eq. (8) can be simplified as

$$\frac{2\xi}{d-\xi} - 1 = 0 \qquad (9)$$

Solving Eq. (9), we obtain:

$$\xi = \frac{1}{3}d \quad \text{or} \quad \Delta = \frac{\xi}{d} = \frac{1}{3} \qquad (10)$$

Discussion: the deflection at the beam's tip cannot exceed 1/3 of the distance between two adjacent electrodes. Otherwise, an excess deflection at the tip of the beam, and a short circuit between two adjacent electrodes will occur. By inserting Eq. (10) into Eq. (6), the formula of the threshold voltage is as follows.

$$V_{th} = 0.6476\,\frac{(td)^{\frac{3}{2}}}{l^2}\left(\frac{2E}{3\epsilon_0}\right)^{\frac{1}{2}}$$

Calculation example: $E = 7.17\times10^{10}\,\mathrm{N/m^2}$, $\epsilon_0 = 8.85\times10^{-12}\,\mathrm{F/m}$, $t = 25\mu m$, $d = 30\mu m$, $l = 5mm$, the threshold voltage V_{th} is obtained to be 39.04V.

4 Conclusion

Based on the mechanical and electric characteristics, the cantilever beam' deflection characteristic is analyzed theoretically, and the quantitative relationship of the applied voltage versus the amount of deflection is obtained. According to the theoretical analysis, we derive a formula of the threshold voltage The applied voltage, having no connection with the width of the beam, is in inverse proportion to the square of the beam's length. The deflection at the beam's tip can not exceed 1/3 of the distance between two adjacent electrodes. Otherwise, an excess deflection at the tip of the beam and a short circuit between two adjacent electrodes will occur. The calculation results and analyses in this paper are of every significance to the development of the devices and the micromechanical optical switches.

References

[1] C. R. Giles, V. Aksyuk, B. Barber, R. Ruel, L. Stulz and D. Bishop, A Silicon MEMS Optical Switch Attenuator and its Use in Lightwave Subsystems, IEEE Journal of Selected Topics in Quantum Electronics, 1999, **5**(1): 18—25.

[2] L. Y. Lin, E. L. Goldstein and R. W. Tkach, Free-Space Micromachined Optical Switches for Optical Networking, IEEE Journal of Selected Topics in Quantum Electronics, 1999, **5**(1): 4—9.

[3] Shi-Sheng Lee, Long-Sun Huang, Chang-Jin Kim and Ming C. Wu, Free-Space Fiber-Optic Switches Based on MEMS Vertical Torsion Mirrors, Journal of Lightwave Technology, 1999, **17**(1): 7—13.

[4] WEI Hong-zhen, YU Jin-zhong, LIU Zhong-li and WANG Qi-ming, Recent Progress in Research on Silicon-Based Optical Waveguide and Switches, Semiconductor Optoelectronics, 1999, **20**(6), 369—376[魏红振, 余金中, 刘忠立, 王启明, 硅基光波导及光波导开关的研究进展, 半导体光电, 1999, **20**(6): 369—376].

[5] T. Kominato, Y. Ohmori, H. Okazaki and M. Yasu, Very Low-Loss GeO_2-Doped Silica Waveguides Fabricated by Flame Hydrolysis Deposition Method, Electronics Letters, 1990, **26**(5): 327—328.

[6] B. H. Verbeek, C. H. Henry, N. A. Olsson, K. J. Orlowsky, R. F. Kazarinov and B. H. Johnson, Integrated Four-Channel Mach-Zehnder Multi/Demultiplexer Fabricated with Phos-

phorous Doped SiO_2 Waveguides on Si, Journal of Lightwave Technology, 1988, **6**(6): 1011—1015.

[7] GONG Zhi-yu and LI Zhang-zheng, Material Mechanics, Beijing: Chinese Science Press, 1999[龚志钰, 李章政, 材料力学, 北京: 科学出版社, 1999].

[8] R. Bruckner, J. Non-Cryst. Solids, 1970, **5**: 123.

一种微机械光开关的分析和设计

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摘要: 对悬臂梁微机械光开关的机电特性进行了理论分析. 利用机械和电学特性, 导出了悬臂梁的弯曲量和所加的电压的解析关系, 并给出了阈值电压的计算公式. 指出外加电压与梁的宽度无关, 与梁的长度的平方成反比. 悬臂梁尖端的弯曲量不能超出相邻电极间距的 1/3. 这些结论是悬臂梁微机械光开关设计和研制的直接依据.

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