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Advancements and Challenges in Photomask Technologies for Semiconductor Lithography: A Comparative Review of Binary, Phase-Shift, and EUV Masks

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Abstract:

This report investigates essential photomask technologies in semiconductor manufacturing and their developments. It outlines the principles and uses of binary photomasks, attenuated phase shift masks, and extreme ultraviolet (EUV) photomasks in lithography systems. With technological advancements, masks have evolved to tackle the demand for smaller feature sizes. Despite these advancements, each mask type has specific applications and constraints. The report also touches on other mask types, including ternary, chromeless phase lithography (CPL), and silicon-containing masks, and anticipates future challenges and directions in photomask technology.

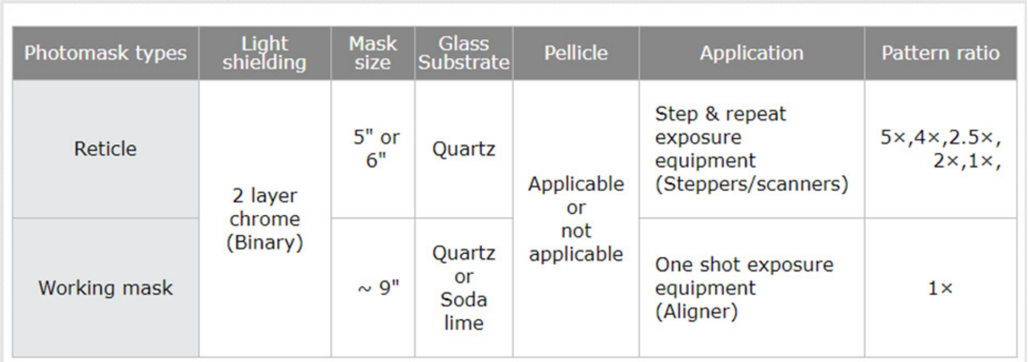
Keywords: Photomask Technologies, Semiconductor Lithography, Binary, Phase-Shift, EUV Masks

I. Introduction

In the intricate world of semiconductor manufacturing, photomasks play a pivotal role. They are the blueprints that guide the light in photolithography systems, etching out the complex patterns of circuits on silicon wafers. The variety of photomasks available today is a testament to the relentless innovation in this field, each type tailored to meet specific needs and challenges in semiconductor fabrication. This paper mainly introduces binary photomask, phase-shift photomask, and EUV photomasks. Other photomask including ternary photomask, CPL photomask, and silicon stencil photomask will have a simple illustration in this report paper.

II. Binary Photomask

Binary photomask is a critical and basic component in the photolithography process used in the production of integrated circuits. It has a simple structure with a transparent substrate and an opaque layer. The transparent substrate is usually made of quartz or soda lime. From the datasheet of Tydex, quartz has a high-level of optical transmittance between 0.15um and 4.35um [1]. The opaque layer is usually made of Chrome. Thus, the transmission characteristics of it can only be transparent or non-transparent. It is also why it is called "binary". The standard size of a binary photomask is 6*6 inches, but various sizes can be made to meet specific needs. Figure1 shows binary photomask products of Nippon Filcon in different sizes [2]. The reticle and working photomask are two types of binary photomask with different pattern ratio or reduction ratio. This ratio affects relationships between the size of the pattern on photomask and it on the wafer.



Photomask types	Light shielding	Mask size	Glass Substrate	Pellicle	Application	Pattern ratio
Reticle	2 layer chrome (Binary)	5" or 6"	Quartz	Applicable or not applicable	Step & repeat exposure equipment (Steppers/scanners)	5×,4×,2.5×, 2×,1×,
Working mask		~ 9"	Quartz or Soda lime		One shot exposure equipment (Aligner)	1×

Figure 1 product size of binary photomasks in Nippon Filcon[2]

The working operation of a binary photomask is controlling the transmittance of light. Light passes through the transparent quartz areas and is blocked by the opaque chrome areas. Where the light hits the wafer, the photoresist is exposed, and those areas are later removed in the development process, leaving the unexposed areas as features on the wafer. One important technology in using binary photomask is scaling. The scale of the photomask will affect the intensity of light passed onto the wafer. As shown in Figure2, the resolution of the image on the wafer is better for larger contrast in light intensity [3].

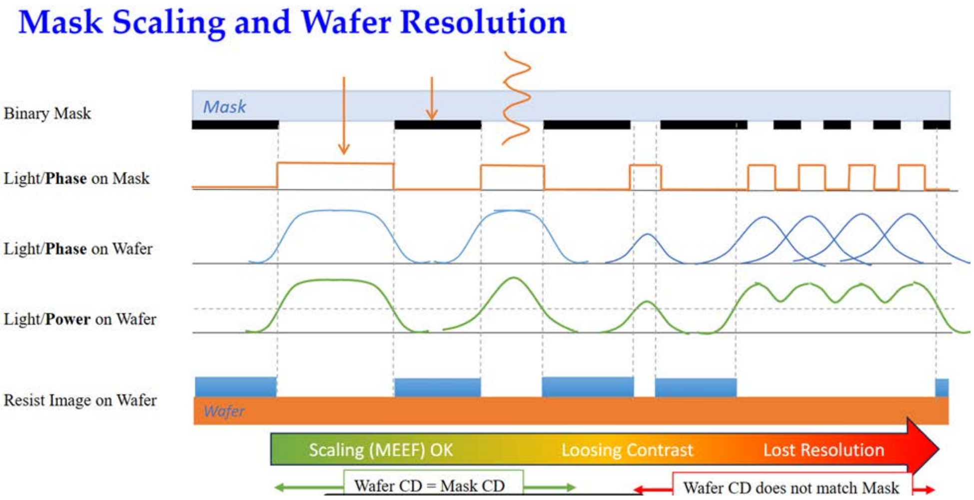


Figure 2 mask scaling and wafer resolution [3]

In all, binary photomasks have advantages in simplicity, material, and resolution. Binary masks are still used for building a pattern in which line width is larger than the exposure wavelength. First, the simple structure of it masks it relatively easier to design. Second, the quartz or soda lime used for transparent substrate has high-level transmittance and low thermal expansion rate. Third, for DUV of wavelength between 246 nm and 193 nm, the binary photomask improves resolution on wafer by reduced minimum feature size.

However, as the wavelength used for the photolithography process becomes smaller, the feature size required shrinks. The binary photomask can achieve a smaller feature size by scaling the size of the pattern. However, as the scale on masks shrinks, the light intensity will start to lose contrast. This will lead to a loss in resolution. As shown in Figure2, the resolution will completely lose when scale is too small and no contrast in light intensity[3]. There are several solutions to it. They are all called resolution enhancement technologies (RET). Optical Proximity Correction is one of the significant technologies used to compensate for resolution by reducing optical error. By doing line biasing, the optical error induced by the end line is fixed. Another method is called Scattering bars. The “bars’ ‘ are thin lines that will not have images on wafer but will sharpen the image by scattering light. Based on these technologies, the binary photomask can reach a limit of 198 nm feature size [4].

III. Phrase-shift Photomask

Phase-shift mask (PSM) technology represents a pivotal enhancement over binary masks in the field of photolithography. By using the principle of light interference, it enhances resolution and image contrast. This improvement is crucial for distinguishing very small features as devices become more compact and their components shrink in size.

PSMs enhance imaging by incorporating both phase and amplitude details in their design. Traditional binary masks use chrome to define where the edges of the resist should be, blocking light completely. PSMs apply the concept that light changes phase when it travels through a material, with the amount of change depending on the material’s optical thickness. Consequently, light traversing a certain thickness of quartz will emerge with a phase shift different from light passing through air.

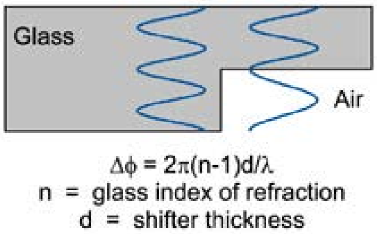


Figure 3 Phase-Shift Masks [5]

By precisely adjusting the quartz layer’s thickness, PSMs can create a desired phase shift. Setting this shift to 180 degrees allows for sharper images and a greater depth of focus. This is because light from parts of the mask that have been phase-shifted will destructively interfere with light from non-shifted areas at the image plane, effectively canceling out when the shift is exactly 180 degrees and the light intensities are balanced. A phase edge created by a 0-180° shift on the mask will appear as a finely printed dark line. Utilizing a series of these edges enables the printing of very narrow line and space patterns.

The most prevalent PSM types include alternating and attenuated masks. However, practical use of PSMs is constrained by issues such as phase termination and the complexities involved in mask production.

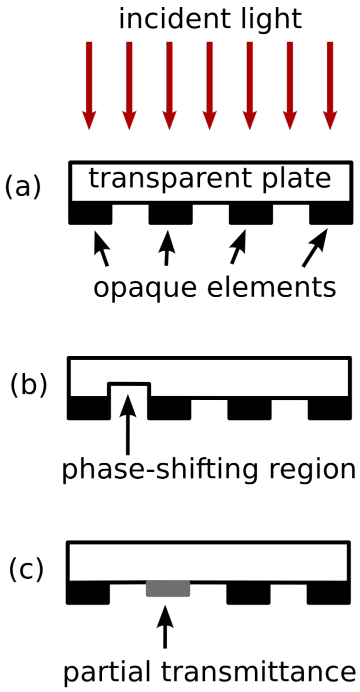


Figure 4 A schematic illustration of various types of masks: (a) a conventional (binary) mask; (b) an alternating phase-shift mask; (c) an attenuated phase-shift mask. [6]

Alternating Phase-shift Photomasks (AltPSMs) employ a robust phase-shifting methodology that significantly elevates image contrast and focal depth for dense line patterns[7].The technology, however, is not without limitations; challenges include phase conflicts and diminished amplitude transmittance, which arise from the subtractive etching processes required for mask production. Strategies to mitigate these issues, such as biasing etch dimensions, are only partially effective.

Attenuated Phase-shift Photomask (EPSM), characterized as “weak” shifters, allow a modicum of light transmission through phase-shifting regions. While they fall short of AltPSMs in resolution enhancement, their simpler manufacturing process and adaptability from existing designs make them a pragmatic choice in certain lithographic applications.

In transition to high-NA EUV lithography, the continued scaling of semiconductor devices introduces a series of significant challenges. First of all, the utilization of low-n materials such as ruthenium and platinum for phase-shift masks is impeded by their etching resistance. This resistance complicates the mask production process and demands new etching technologies. Second, mask-making resistance development is demanded. As feature sizes decrease below the 20nm threshold, the current resist materials prove inadequate. A resist that maintains structural integrity at these dimensions and exhibits the necessary resolution is essential such as metal-oxides type material [8].

In summary, PSM technology significantly advances photolithography by enabling the printing of extremely small features necessary for modern semiconductor devices. Although both AltPSMs and EPSMs offer notable improvements in resolution and focus, they face manufacturing and design challenges that must be addressed. As the industry progresses towards high-NA EUV lithography, innovations in mask materials and etching processes are critical to meet the demands of increasingly finer scales.

IV. EUV Photomask

EUV is a number one candidate for next generation lithography technique. EUV lithography uses EUV light (13.45nm), shorter wavelength than existing DUV (ArF: 193 nm), which enables us to fabricate smaller patterns. Unlike conventional DUV, EUV lithography requires reflective optics for wafer exposure systems.

Bragger layer

One EUV light has been generated, it must be focused and directed to the EUV photomask and then to the silicon itself. It turns out a special type of mirror is needed to reflect EUV light, the Bragg reflector, which is made up of many alternating layers of molybdenum and silicon[9].

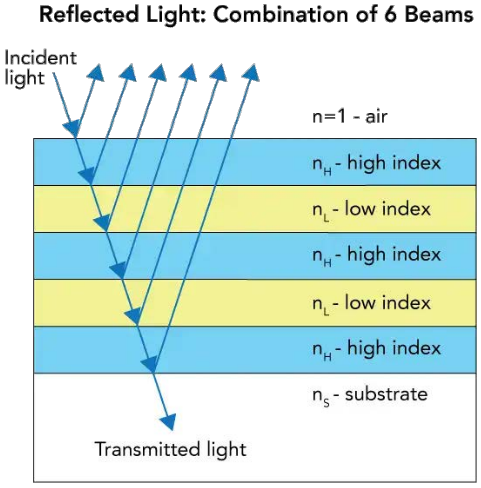


Figure 5 Bragger Layer [9]

The reason Mo/Si is a popular choice is due to the contrast in their optical properties, which leads to constructive interference in the reflected light from the multiple interfaces.

Structure of EUV Photomasks

Notice how there is an “absorber” at the top of the photomask. EUV light gets reflected from the Bragg reflector mirror and is partly stopped by the absorber. EUV light is only absorbed where the absorber is present, while it is reflected onto the wafer where the absorber is not.

The inclusion of Ru capping in EUV photomasks provides a safeguarding coating that protects the important Mo/Si multilayer structure from environmental damage.

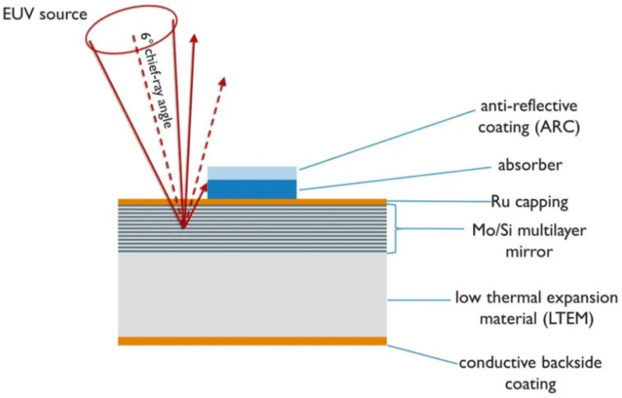


Figure 6 EUV photomask side view[10]

The Mo/Si multilayer mirror is the Bragger layer which is described in the previous paragraph.

The photomask’s bottom section comprises materials with low thermal expansion and a conductive backside coating. The use of low thermal expansion materials guarantees dimensional stability during exposure to high temperatures in the EUV lithography process. Additionally, the conductive backside layer safeguards the EUV mask against possible electrostatic discharge (ESD) damage.

Challenge for EUV Photomasks

In addition to the EUV light required for patterning, the light also contains unnecessary wavelengths, called out-of-band (OOB) light[11]. The OOB light negatively impacts the accuracy of forming sections surrounding the pattern on silicon substrates.

The full mirror reflects only 70% of the light, making it a lossy reflector. To focus and direct the EUV light, the EUV machine needs a series of mirrors, usually between 6 to 12. Combined with the lossy plasma excitation process, energy loss poses a serious concern as only 1-5% of the input energy reaches the wafer[9].

The accumulation of tin splatter over time also causes trouble dealing with EUV machines, which eventually leads to degraded performance, needing expensive maintenance.

Potential Solutions

To deal with the OOB problems, a photomask manufacturing company called Toppan has developed a special three-dimensional structure on the light-shielding black border of the mask, enabling better control of light from the light source.

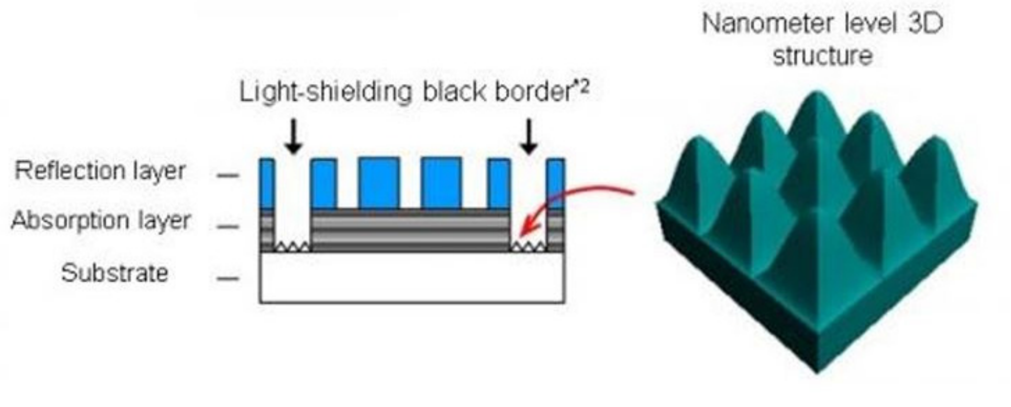


Figure 7 light-shielding black border[11]

Transfer testing utilizing EUV exposure machinery produced by ASML*3 has confirmed that this novel EUV photomask can lessen dimension variability on silicon substrates by 66%[11]. Consequently, it facilitates advancements in quality and yield for semiconductor designs.

V. Other Photomasks

This section will provide a brief introduction to three specialized types of photolithography masks: Ternary Masks, Chromeless Phase Shift Lithography (CPL) Masks, and Silicon Stencil Masks.

Ternary photomask

Compared to the conventional Binary Photomask, the Ternary Photomask allows for three different levels of exposure intensity in a single exposure process, namely high light intensity transmission, medium light intensity transmission, and low light intensity transmission. The figures below illustrate the structure and effect of the Ternary Photomask.

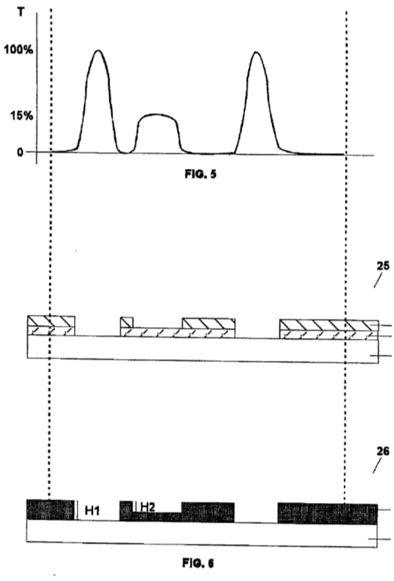


Figure 8 Ternary Photomask Effectiveness Illustration [12]

Among the three different light intensity areas, the highlight areas do not produce any phase difference due to the photomask, allowing the light to create the strongest exposure effect directly on the photoresist. The medium-light intensity areas typically contain phase-shifting materials for light, inducing a certain phase difference during transmission. Owing to the interference properties of waves, some of the light waves are canceled out during transmission, resulting in medium-intensity exposure on the photoresist. The low-light intensity areas are usually composed of opaque materials, capable of blocking most of the light, leading to the weakest or no exposure effect in these areas.

Chromeless Phase Shift Lithography (CPL) Masks

The special feature of the Chromeless Phase Shift Lithography (CPL) mask is that it does not use any chrome or other opaque materials. Below is an illustration of the working principle and effect of CPL.

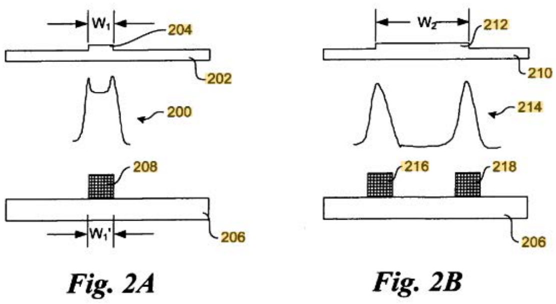


Figure 9 CPL Mask Effectiveness Illustration [13]

On a CPL photomask, variations in the thickness and refractive index of transparent materials cause phase differences in the light as it passes through. During this process, CPL utilizes the destructive interference effect produced at the edges of 0-degree and 180-degree phase-shifted light. This effect ensures that the corresponding areas are not cleared in subsequent processing, thereby forming the required pattern.

Silicon Stencil photomask

The Silicon Stencil Mask is a type of mask specifically used for X-ray lithography. Compared to other materials, silicon, typically 200 micrometers thick, can block sufficiently strong X-rays[14]. The following image shows the exposure pattern of a Silicon stencil photomask under specific conditions.

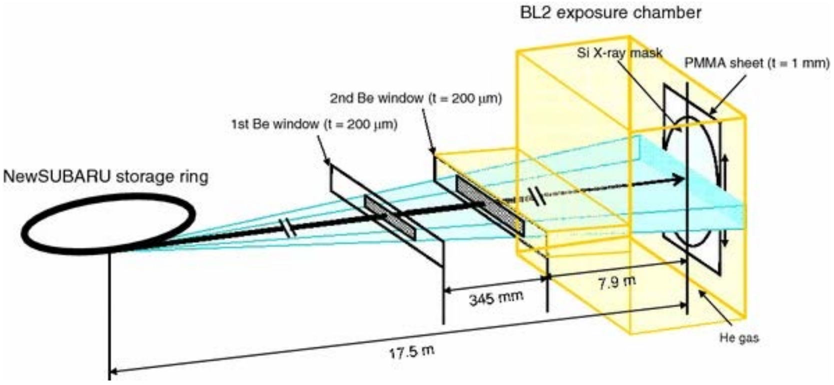


Figure 10 Stencil Silicon Mask Effectiveness Illustration [14]

Silicon stencil mask X-ray lithography is similar to traditional lithography. In X-ray lithography, the silicon stencil mask is placed on the photosensitive resin. During exposure to X-rays, the silicon stencil mask effectively blocks parts of the X-rays, thereby creating patterns on the photosensitive resin.

VI. Conclusion

In conclusion, an examination of current photomask technologies reveals their pivotal role in advancing semiconductor fabrication. From basic binary masks to intricate phase-shifting masks, and onto cutting-edge extreme ultraviolet (EUV) masks, each technology plays a critical part in addressing the challenges of fine pattern delineation in lithography. While each mask type has its specific applications and limitations, the continuous evolution in microelectronics demands further development and innovation in mask technology. Looking ahead, we anticipate breakthroughs in mask technologies that will sustain the relentless progress in the microelectronics industry.

VII. Acknowledgment

In this report, each member conducts research on a specific type of photomask. Dongyang Li researches EUV photomask, Bill Wang researches Binary photomask and the introduction section, Yunhan Xing researches Phase-shifting photomask, and Yan Ren researches other types of photomask and concludes the report.

VIII. REFERENCES

[1] TYDEX, ‘Synthetic Crystal Quartz,’ TYDEX. [Online]. Available: http://www.tydexoptics.com.

[2] Filcon, ‘Product Size,’ Filcon Photomask. [Online]. Available: https://filcon-photomask.com/en/product/size.php.

[3] J. Rankin. IBM Research, “Lec06-Litho_Photomasks_JRankin”,[Online]. Available: https://rpi.app.box.com/s/iaurgqw1cima5m7166olpfianewzl039

[4] Yoshioka, ‘Advanced Mask Inspection and Metrology’ National Institute of Standards and Technology, 2003. [Online]. Available: http://www.nist.gov/Yoshioka_2003.pdf.

[5] SPIE. “Phase-Shift Masks.” spie.org. https://spie.org/publications/fg06_p78-80_phase-shift_masks?SSO=1 (accessed Oct. 26, 2023).

[6] O. Alexandrov. “This W3C-unspecified vector image was created with Inkscape.” Public Domain, https://commons.wikimedia.org/w/index.php?curid=2883165

[7] H. Kirchauer. “2.4.2 Phase-Shifting Masks.” Institute for Microelectronics. https://www.iue.tuwien.ac.at/phd/kirchauer/node24.html (accessed Oct. 26, 2023).

[8] M. Lapedus. “Photomask Challenges At 3nm And Beyond.” semiengineering.com. https://semiengineering.com/photomask-challenges-at-3nm-and-beyond/ (accessed Oct. 26, 2023).

[9] B. Ramsundar. “The Physics of EUV Lithography.” substack.com. https://deepforest.substack.com/p/the-physics-of-euv-lithography (accessed Oct. 26, 2023).

[10]Cross-section of an EUV mask. In EUV, light hits the mask at an angle of 6°. Source: Luong, V., Philipsen, V., Hendrickx, E., Opsomer, K., Detavernier, C., Laubis, C., Scholze, F., Heyns, M., “Ni-Al alloys as alternative EUV mask absorber,” Appl. Sci. (8), 521 (2018). (Imec, KU Leuven, Ghent University, PTB)

[11]TOPPAN. “Toppan Printing develops next-generation EUV photomask for leading-edge semiconductors.” toppan.com. .https://www.holdings.toppan.com/en/news/2016/02/newsrelease160224.html (accessed Oct. 26, 2023).

[12] P. Coronel, O. Richard, and D. Rigaill, “Ternary photomask and method of making the same,” U.S. Patent US20020012851A1, January 31, 2002.

[13] S. Sivakumar and P. Nyhus, “Chromeless phase shift lithography (CPL) masks having features to pattern large area line/space geometries,” U.S. Patent 7179570B2, Feb. 20, 2007.

[14] H. Mekaru, T. Takano, Y. Ukita, et al., “A Si stencil mask for deep X-ray lithography fabricated by MEMS technology,” Microsyst. Technol., vol. 14, pp. 1335–1342, Oct. 2008. doi: 10.1007/s00542-007-0513-z.