Sensors and Actuators A 155 (2009) 23–32

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design and demonstration of PECVD multilayer dielectric mirrors optimized for micromachined cavity angled sidewalls☆

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ARTICLE INFO

Article history:
Received 16 July 2008
Accepted 13 October 2008
Available online 25 October 2008

PACS:
07.07.Df
33.25.+k
42.79.Fm
42.82.Bq
85.85.+j

Keywords:
Atomic MEMS
Bragg reflector
Optical MEMS
PECVD
Thin films
Vapor cells

ABSTRACT

This paper reports on the design and implementation of high efficiency, nonmetallic reflectors integrated on the sidewalls of micromachined cavities. Due to shadowing from deposition within a cavity, significant variation in the thicknesses of the dielectric thin films composing the reflectors are encountered when the layers are deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD). These gradients in thickness limit the performance of the reflector at the intended design wavelength. An optimized design procedure is described to maximize the performance of the reflector at the D_1 absorption wavelength of ^{87}Rb of 795 nm for use in micromachined atomic vapor cells. The reflector design is based on multiple shifted quarter wave Bragg reflectors in series, which extends the reflective bandwidth for increased robustness to film thickness gradients. The extended reflectance range maintains high reflection at the design wavelength despite greater than 70% decrease in film thickness across the reflector surface. The reflector technology is ideally suited for use in atomic MEMS vapor cell applications by achieving high reflectance while maintaining light polarization. We demonstrate less than 2 dB of return loss with circular polarization ellipticity maintained to $\pm 2^{\circ}$.

1. Introduction

Miniature vapor cells for emerging atomic MEMS applications, such as chip scale atomic clocks [1], magnetometers [2,3] and gyroscopes, depend on the efficient routing of laser light by use of micromachined reflectors. Cells containing rubidium alkali vapor need low reflection losses at the ^{87}Rb D_1 transition wavelength of 795 nm after multiple reflections inside the vapor cell cavity formed in bulk micromachined wet-etched silicon, as shown in Fig. 1. Vapor cells designs with integrated reflectors enable the implementation of compact atomic MEMS systems. For instance, the vapor cell probe beam may be emitted by a vertical cavity surface emitting laser (VCSEL) and interrogated by a photocollector such that both opto-electronic components are integrated as discrete components on a single electronics plane.

However, uncoated silicon is not sufficiently reflective for use as a high performance mirror, as it loses more than 2/3 of incident optical energy in bulk transmission. Previously, rubidium vapor cells with optical return performance superior to uncoated silicon have been demonstrated by use of multilayer dielectric reflectors integrated on the sidewalls of wet-etched silicon cavities fabricated by use of Plasma Enhanced Chemical Vapor Deposition (PECVD) [4]. Although these reflectors have the potential to reflect light with negligible loss, large variations in the thin film thicknesses were observed due to the deposition technology that limited the reflector performance.

PECVD has many practical advantages over other thin film fabrication methods, such as Physical Vapor Deposition (PVD), including higher deposition rates and the formation of films with better mechanical and environmental robustness [5]. However, the thicknesses of PECVD fabricated thin films deposited onto the sidewalls of micromachined cavities rapidly decrease with cavity depth. This film thinning is due to the decrease in the arrival angle available to reactant species (shadowing) from the PECVD reactor chamber [6]. Previously, the effects of such film thinning has been observed

☆ This paper is part of the Special Section of the Micromechanics Section of Sensors and Actuators based on contributions revised from the Technical Digest of the 2008 Solid-State Sensors, Actuators and Microsystems Workshop sponsored by the Transducer Research Foundation, Inc. (1–5 June 2008, Hilton Head Island, South Carolina, USA).

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2008.10.007

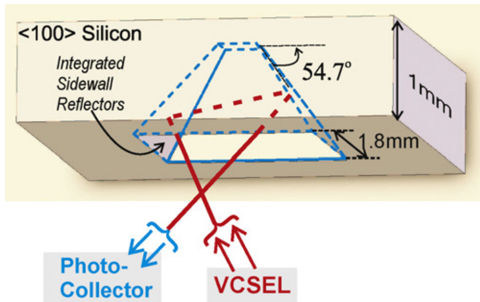

Fig. 1. Bulk micromachined vapor cell with integrated reflectors for atomic MEMS.

on multilayer reflectors deposited on shallowly etched substrate facets intended for use with integrated optoelectronic components [7]. However, reflectors integrated into deeply etched cavities, such as required for atomic MEMS vapor cells, present significant challenges in maintaining reflector uniformity when PECVD is used. For the vapor cell geometry previously proposed in [4], the nonuniformity represents a reduction in layer thickness by more than 70% from the top to the bottom of all of the faces of the cavity sidewalls. The film nonuniformity results in an optical shift of the reflection spectrum of the integrated Bragg reflector to wavelengths below the design wavelength. In this work, a thin film reflector design methodology is described and demonstrated that maintains high reflectance at the design wavelength in the presence of these challenging deposition conditions.

An example of one such optimized reflector deposited on the angled sidewalls of a wet bulk micromachined cavity is shown in Fig. 2. When the multilayer reflector is deposited on the angled cavity sidewalls, thinning of the film from top to bottom of the cell results in a shift in the reflection to lower wavelengths. The reflectance shift is visible to the naked eye by the color change of the reflector face from red to yellow to blue down the sidewall face. In conventional Bragg reflector designs, since the optimum reflectance wavelength varies over the area of the reflector, the efficiency at the design wavelength is compromised.

In the case shown in Fig. 2, an advanced thin film reflector design is applied to extend the range of the high reflectance band, and the deposition process is optimizing for the intended application wavelength. This design and fabrication process maximizes the reflectance down the cavity sidewall at the design wavelength.

This paper describes the design and demonstrates the potential of PECVD reflectors for integration onto the sidewalls of micromachined cavities for atomic MEMS applications. This work is an expansion of the preliminary results presented at the 2008 Hilton Head Solid-State Sensors, Actuators and Microsystems Workshop

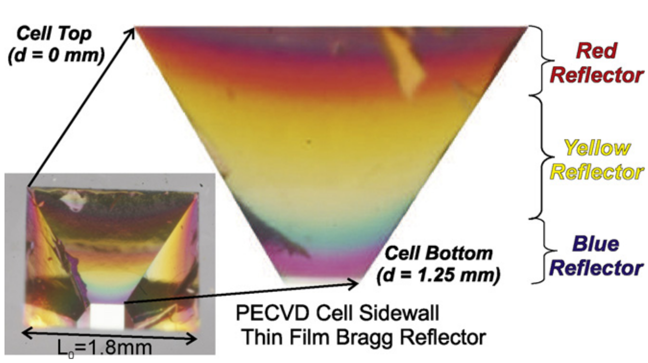

Fig. 2. Optimized extended 12 layer ($6 \times |\alpha Si\, SiO_2|$) PECVD Bragg reflector on the sidewall of a reflector cell with shifting wavelength reflectance (red to yellow to blue) due to deposition nonuniformity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

[8]. In Section 2, the design of sidewall integrated Bragg reflectors is presented. This section includes the effects of cavity shadowing, optimized design for sidewall integration, the use of the reflector bandwidth to estimate robustness to thinning of the reflector films and the design of Bragg reflectors with extended reflectance bandwidth. Section 3 models the response of both conventional and extended bandwidth reflector designs when integrated on a cavity sidewall and compares the performance. Section 4 describes the specific implementation of the cavity sidewall integrated extended Bragg reflector. Finally, in Section 5 the reflector bandwidth of the extended Bragg reflector is characterized and compared to that of a conventional Bragg reflector, and the performance of the extended Bragg reflector design is evaluated for single and multiple reflections within a reflector cell.

2. Design of PECVD multilayer reflectors for cavity sidewalls

2.1. Bragg reflector bandwidth

The design of micromachined cells with integrated Bragg reflectors for rubidium vapor cells has been previously described in [4]. Briefly, the light reflected at the interface between each layer may be made to constructively interfere to maximize the total reflected optical power at a specific wavelength. The reflectivity is maximized if the structure is composed of alternating thin film layers each of optical thickness equal to one-quarter wavelength of the light to be reflected, as given by [9]

$$t = \frac{\lambda_0}{4n}, \tag{1}$$

where t is the thickness of each layer, λ_0 is the wavelength of light to be reflected and n is the index of refraction of each layer.

The high reflectance wavelength bandwidth is given by [9]

$$2\Delta g = \frac{4}{\pi} \sin^{-1}\left(\frac{n_H/n_L - 1}{n_H/n_L + 1}\right), \tag{2}$$

where g is the normalized wavenumber ($g = \lambda_0/\lambda$) and n_H is the higher and n_L the lower index of refraction of each of the thin film materials. The wavelengths at the upper (λ_+) and lower (λ_-) limits of this reflectance band are given by

$$\lambda_+ = \frac{\lambda_0}{1 - \Delta g} \tag{3}$$

for the wavelength at the upper limit and

$$\lambda_- = \frac{\lambda_0}{1 + \Delta g}, \tag{4}$$

for the wavelength at the lower limit, which yields the reflector bandwidth $\Delta\lambda$ in wavelength units given by

$$\Delta\lambda = \lambda_+ - \lambda_- = \frac{2\Delta g}{1 - (\Delta g)^2}\lambda_0. \tag{5}$$

The effect of increased index of refraction contrast n_H/n_L between the thin film pairs $|n_H\, n_L|$ on (2) and (5) are shown in Fig. 3. For low contrast materials, the normalized reflector bandwidths expressed by $2\Delta g$ and $\Delta\lambda/\lambda_0$ are numerically identical. However, for reflectors formed with high contrast materials, the differences become significant (10% at $n_H/n_L = 2.7$). Overlayed are the expected reflector bandwidth that may be obtained with thin film materials readily deposited using PECVD, as tabulated in Table 1. It may be readily observed that the width of the reflectance band is maximized by use of high contrast ratio materials.

Amorphous silicon (αSi) and silicon dioxide (SiO_2) yield the highest optical index contrast available ($n_H/n_L = 2.7$, $\Delta g = 0.3$), such that for $\lambda_0 = 795$ nm, $\Delta\lambda = 520$ nm. Reflector bandwidth of integrated cavity sidewall reflectors as wide as $\Delta\lambda = 500$ nm has