Towards MEMS-based Long-wavelength Infrared Tuneable Fabry-Perot Filters

Haifeng Mao, Mariusz Martyniuk, Dilusha Silva, Jarek Antoszewski, John Bumgarner, Lorenzo Faraone

***Abstract*—This paper describes the realization of LWIR (8-12 μm) Fabry-Perot filters on basis of our previously demonstrated SWIR (1.6-2.5 μm) or MWIR (3-5 μm) filter technique. An innovative filter design employing a single layer of Ge as the top mirror is proposed and optical modelling shows that the filter can potentially achieve spectral characteristics required by the LWIR spectral imaging applications. As a proof of concept, filters with fixed air cavity were fabricated and bowing in the suspended mirror was corrected by depositing a thin SiN_x stress compensation layer underneath the mirror. Transmission measurement was carried out on the filter exhibiting the least bowing, despite some spectral degradation compared to the theoretical model of the filer, showing not optimal but adequate transmission and bandwidth for multispectral imaging applications.**

***Index Terms*—Fabry-Perot filters, Long-wavelength infrared(LWIR), Micro-electromechanical systems (MEMS)**

I. Background

State-of-the-art infrared (IR) focal plane array (FPA) technologies aim to improve the performance of IR imaging systems by adding so-called multi-colour capability, which allows on-pixel information to be gathered from two or more spectral regions. Spectral information allows improved target recognition and reduced false alarm rates in military applications, and accurate temperature determination in civilian applications. Conventional multispectral imaging devices manipulate a set of interferometric filters mounted in a rotating wheel optically in front of the detector to realize spectral selectivity and are typically characterized by significant size and cost, which prohibit them from many desirable applications. The approach chosen by the Microelectronics Research Group (MRG) at the University of Western Australia is to develop a micro-electromechanical systems (MEMS) technology that is compatible with large format two-dimensional infrared FPAs. The device structure consists of an electrostatically controlled MEMS-based Fabry-Perot filter that is integrated optically in front of the detector array and is illustrated in Fig. 1 [1]. Electrostatic actuation allows the top mirror to be moved downwards, thus decreasing the mirror spacing and, thereby, spectrally shifting the optical pass-band of the filter. Each mirror is a distributed Bragg reflector (DBR) consisting of three layers, Ge-SiO-Ge. A structural layer of SiN_x is used to support the top mirror, and further extends to the support arms that actuate the mirror structure. Another SiN_x layer is deposited underneath the mirror to balance the stress and therefore eliminate mirror buckling. An attractive feature of this filter structure is horizontal scalability, making it compatible with implementation as a single filter covering the entire array, or as an array of filters on a per-pixel level at the focal plane. Past work has focused on short-wavelength infrared (SWIR, 1.6-2.5 μm) [1] and mid-wavelength infrared (MWIR, 3-5 μm) bands [2]. This paper primarily focuses on the extension of this technology to filters in the long-wavelength infrared (LWIR, 8-12 μm) band. The LWIR is the "thermal imaging" region, in which sensors can obtain a completely passive picture of the outside world based on thermal emissions only and requiring no external light or thermal illuminating sources such as the sun or moon, as required for demanding "night vision" applications.

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II. Implementation

A. Filter Design and Modelling

Although Ge is an ideal optical material to use in the LWIR band, SiO is far too absorbing to be of any use. Therefore, the mirrors need to be redesigned using a less absorbing material. In this work, to replace the SiO, we use ZnS as a low-index non-absorbing medium for the mirrors. In addition to wide-band transparency, Ge and ZnS also combine high refractive index contrast (in LWIR band, the refractive indices of Ge and ZnS are 4 and 2.2, respectively [3]). Standard sapphire and Czochralski (CZ) silicon substrates are excessively absorbing in the LWIR band. As such, the substrates used for fabricating LWIR devices are float-zone (FZ) silicon.

In previous SWIR or MWIR filter development, multi-layer nature of the top DBR mirror gives rise to significant stress mismatch in the top mirror that requires great effort to be managed, or otherwise it highly deforms the top mirror and degrades filter performance. The issue is compounded in the LWIR case because the longer infrared wavelengths require much thicker optical layers. To overcome this issue, we have designed a Fabry-Perot filter comprised of a movable quarter-wave single-layer Ge top reflector instead of a Ge-ZnS-Ge one and a fixed FZ silicon substrate incorporating a quarter-wave Ge-ZnS-Ge-ZnS bottom reflector, where the Ge and ZnS layer thicknesses are 625 nm and 1130 nm, respectively. Tuning spectra with variable air cavity length, d, are modeled using the transmission matrix method [4] and shown in Fig. 2. The proposed filter is capable of achieving

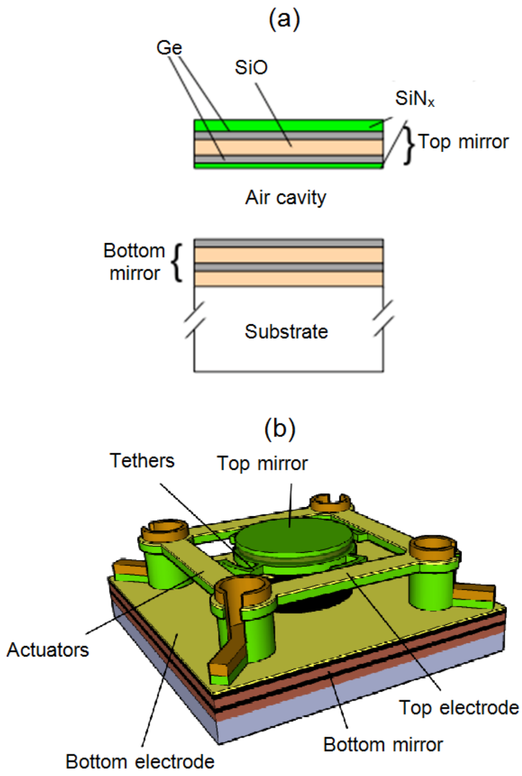

Fig. 1. (a) Cross section of optical and structural layers of MRG microspectrometer, (b) 3D view of micromachined Fabry-Perot filter [1]. The Fabry-Perot filter is composed of two Bragg reflectors realised using alternating layers of Ge and SiO. The discriminated wavelength is determined by the spacing between the top and bottom reflectors. The top reflector is supported by a suspended SiN_x membrane connected to four top electrostatic actuation electrodes. Electrostatic actuation is used to vary the position of the top reflector, thus providing a means of controlling the cavity length and resulting in wavelength tuneability. An underlying IR detector (not shown) senses only photons of the discriminated wavelength.

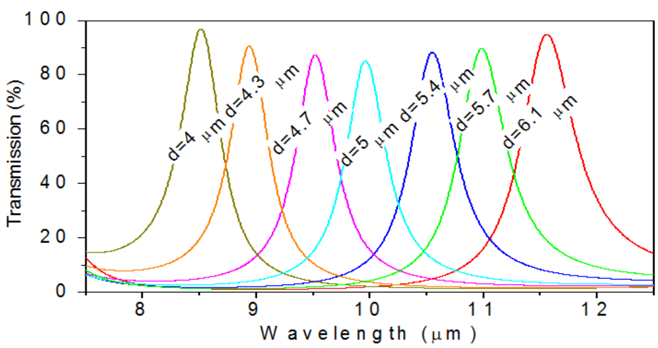

Fig. 2. The modeled tuning spectra of the proposed LWIR Fabry-Perot filter. The filter consists of a single layer of Ge (625 nm) as the top mirror and two periods of Ge (625 nm)/ZnS (1130 nm) as the bottom mirror, cavity formed between the two mirrors varies from 6.1 µm to 4 µm. Refractive indices of 4 and 2,2 for Ge and ZnS [3], respectively, are used in optical modelling.

bandwidths of about 0.5 µm, peak optical transmission higher than 85%, and out-of-band rejection greater than 40:1 across the entire 8-12 µm LWIR wavelength band, which adequately fulfills the performance requirements of the tuneable filter for multispectral imaging applications [5].

Although it is a less significant problem for the LWIR band in comparison to the SWIR and MWIR, stress in single-layer Ge mirror and the resultant mirror bowing can't be ignored as it still causes degradation in filter performance. It has been demonstrated in our SWIR and MWIR filters that a 50 nm thick PECVD SiN_x layer deposited underneath the Ge-SiO-Ge mirror can successfully be deployed as a stress compensator to reduce the curvature of the mirror. Considering the highly absorbing nature of SiN_x in the LWIR band, a much thinner SiN_x layer has to be used in order to ensure that no significant absorption occurs, while also providing sufficient stress balancing. As such, SiN_x layer must be highly stressed. In this work, SiN_x with a predetermined compressive stress of 150 MPa was used.

B. Filter Fabrication

In this paper, a prototype filter with fixed air cavity is demonstrated. The fabrication process for LWIR filters is similar to that for SWIR [6] and MWIR ones [2]. It was found that quality Ge films could be deposited via electron beam evaporation at room temperature and durable ZnS films could be deposited via thermal evaporation with the substrate held at 150 °C. First, a Ge-ZnS-Ge-ZnS quarter-wave bottom Bragg mirror is deposited on a FZ silicon wafer, followed by the evaporation of another quarter-wave ZnS layer on the backside of the substrate as an anti-reflection coating. A 40 nm thick gold layer is then deposited and patterned using lift-off on the front side. The purpose of the gold layer is to only allow transmission of light that is incident on the top mirror area and to shield any stray light. It can also potentially act as the bottom electrode for future tuneable filter implementation. Next, a sacrificial polyimide layer is spun on the wafer and fully cured, forming a 6 µm thick cavity. The polyimide is then dry etched in O_2/CF_4 plasma to expose anchor areas with a gently sloping sidewall profile. A few nanometers thin compressively stressed PECVD SiN_x layer is subsequently deposited and patterned to remain underneath the top mirror to balance the stress in the Ge layer. A 625 nm Ge is deposited using E-beam evaporation and patterned using lift-off to serve as the top mirror and the structural layer. Holes in 4 µm diameter are etched through the top mirror using O_2/CF_4 plasma to allow subsequent removal of the sacrificial polyimide layer using an O_2 plasma ashing process and to form a Fabry-Perot cavity. SEM image of the as-fabricated filter including the structural dimensions is shown in Fig. 3.

C. Filter Characterization

In order to achieve the optimal compensation outcomes of the bowing of the top Ge mirror, four filters were fabricated with different deposition times for the SiN_x stress compensation layer: 0, 14, 21 and 28 s, corresponding to layer thickness of 0, 4, 6 and 8 nm, respectively. Center-to-edge bowing of the released filters were measured using an optical profilometer, and the results are summarized in Fig. 4.

As seen in Fig. 4, the filter with no SiN_x stress compensation layer shows a convex center-to-edge bowing of 1.5 µm over the circular area of the top mirror with a diameter of 150 µm. With 4 nm thick SiN_x layer deposited, the top mirror bowing

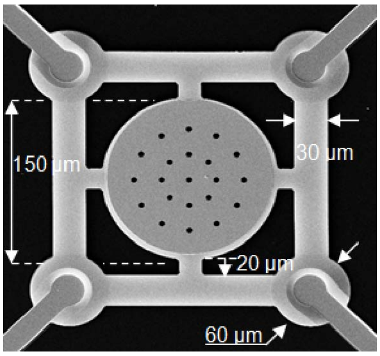

Fig. 3. SEM image of a fabricated LWIR filter and its structure dimension

is significantly reduced to 550 nm. Thicker layers more than 4 nm result in an abrupt change of mirror curvature from convex to concave, mirrors having 6 nm and 8 nm thick SiN_x stress compensation layers feature concave center-to-edge bowing of 600 nm and 750 nm, respectively. A deposition time of approximately 17 s, corresponding to a thickness of 5 nm was found to be optimal to achieve near zero curvature. However, it is expected that run-to-run process variations will overwhelm the attempts to control the SiN_x deposition time to certain seconds. Indeed, filter fabrication using a 17 s deposition time for SiN_x stress compensating layer was undertaken and concave center-to-edge bowing of about 600 nm was obtained for the top mirror.

The optical transmittance of the filter, which exhibited the least convex center-to-edge bowing of 550 nm with SiN_x stress compensation layer thickness of 4 nm, was measured using Fourier Transform Infrared Spectroscopy (FTIR). As evident from Fig. 5, in comparison with 85% peak transmission, 500 nm bandwidth and 40:1 out-of-band rejection predicted for the ideal curvature-free filter, the real filter features an approximately 55% peak transmission, a 700 nm FWHM spectral bandwidth and an 8:1 out-of-band rejection, which are not optimal but adequate for LWIR multispectral imaging applications [5].

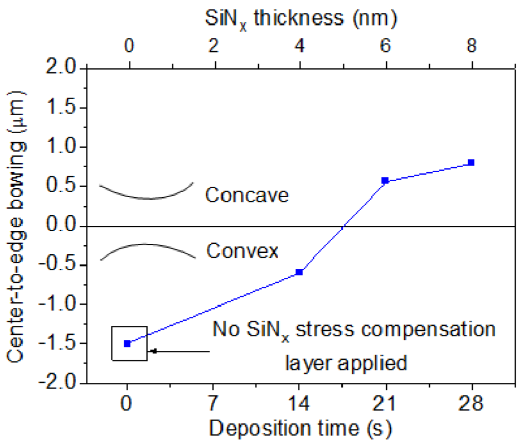

Fig. 4. Center-to-edge bowing of released filter as a function of SiN_x stress compensating layer deposition time. Curvature is as seen from the top.

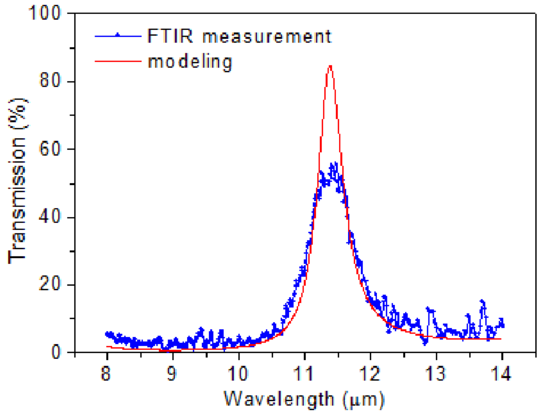

Fig. 5. Optical modelling (red line) of ideal curvature-free filter and FTIR transmission measurement (blue line) of the fabricated filter with 550 nm center-to-edge bowing. Note that 4 nm SiN_x layer is also introduced in the modelling.

III. Conclusions and Future Works

This paper reports on our investigations towards extending our SWIR and MWIR microspectrometer technology to the LWIR band. An innovative LWIR tuneable Fabry-Perot filter consisting of a single-layer Ge as top mirror is proposed with the aim of producing minimally bowed top mirror. The ideal filter is optically modeled to have 85% peak transmission and spectral width of 500 nm across the entire LWIR range, showing promise in being able to achieve the performance requirements of multispectral imaging applications. Prototype filters with fixed air cavity are fabricated using surface micro-machining technology. Top mirror of as-fabricated filter shows a convex center-to-edge bowing of 1.5μm, the deformation is believed to be attributed to stress in Ge layer. As for SWIR filter, approach used to reduce mirror deformation is depositing a SiN_x stress compensation layer. Filter with a 4 nm thick SiN_x compensation layer features the least center-to-edge bowing of about 550 nm and has 55% peak transmission and 700 nm bandwidth, which adequately fulfill LWIR spectral imaging requirements. In order to obtain controllable stress compensation, optimized SiN_x deposition process that will not cause abrupt changes to the mirror curvature needs to be found. Electrostatic actuation mechanism will also be incorporated to manufacture fully tunable LWIR filters.

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