Delft University of Technology

Implementation of CMOS-compatible Metamaterial Absorber for gas Sensing Application

Shahmarvandi, E. Karimi; Ghaderi, M.; Ayerden, P.; de Graaf, G.; Wolffenbuttel, R.F.

DOI
10.1016/j.proeng.2016.11.433

Publication date
2016

Document Version
Final published version

Published in
Procedia Engineering

Citation (APA)
Shahmarvandi, E. K., Ghaderi, M., Ayerden, P., de Graaf, G., & Wolffenbuttel, R. F. (2016). Implementation of CMOS-compatible Metamaterial Absorber for gas Sensing Application. *Procedia Engineering*, *168*, 1241-1244. https://doi.org/10.1016/j.proeng.2016.11.433

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 1241 – 1244

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Implementation of CMOS-compatible metamaterial absorber for gas sensing application

E. Karimi Shahmarvandi, M. Ghaderi, P. Ayerden, G. de Graaf and R. F. Wolffenbuttel

Faculty EEMCS, Delft University of Technology, Mekelweg 4, 2628 CD Delft, Netherlands

Abstract

The design of a metamaterial-based absorber for use in a mid-IR microspectrometer-based gas sensor is reported. The microspectrometer consists of a linear variable optical filter (LVOF) that is aligned with an array of thermopile detectors, which is fabricated on a SiN membrane and covered with the absorber. Special emphasis was put on the CMOS compatible fabrication, which resulted in an absorber design based on aluminium disk resonators and an aluminium background plane that are separated by a SiO_2 layer. The fabrication process is described, and the challenges are discussed.

© 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference

Keywords: *Gas sensing, Microspectrometer, Metamaterial absorber, Mid-Infrared*

1. Introduction

Absorption spectroscopy in the infrared (IR) spectral range is a powerful approach for identifying the composition of a gas [1]. Some of the well-known applications are in breath analysis in disease diagnosis, air quality and atmosferic studies, and home safety. The mid-IR spectral range in between 3.2-3.8μm is particularly useful for the analysis of hydrocarbon combustible gases [2]. The current trend towards a more flexible composition of combustible (natural) gas calls for a low-cost gas sensor to be installed at each burner for a safe and clean combustion [2]. This high-volume application favors a CMOS-compatible MEMS implementation. Figure 1 shows the absorption peaks of hydrocarbons over the infrared spectrum. The particular absorption spectrum for each gas can be used as a fingerprint to identify different gases. The implementation technique proposed is based on a microspectrometer and includes a wideband light source, a gas cell and a Linearly Variable Optical Filter (LVOF) on top of a thermopile detector arrays for analyzing the incident light spectrum after passing the absorption cell. Figure 2 schematically depicts the design of the envisaged gas sensor [3].

1877-7058 © 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.433

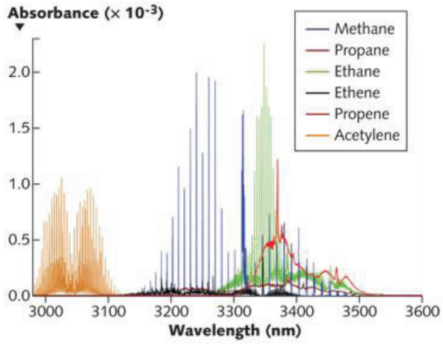
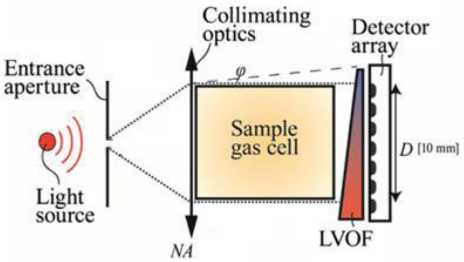
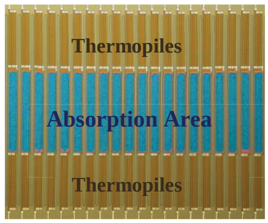


Fig.1. The absorption spectra for different hydrocarbons in mid-IR range between 3-3.6 μm

The implementation of the LVOF is highly promising for high-resolution operation over a short bandwidth which is required for the gas sensing application. However, the out-of-band transmission of the LVOF has to be filtered. This can be achieved by tuning the sensitivity of the detector array using tuneable and sharp absorbers. These requirements turn the absorber into a band-pass filter and making it a critical part of the system design. The conventional techniques for deposition of optical absorbing layers were based on the evaporation of porous metals, use of carbon nanotubes, and multi-film interference filters, which are relatively bulky and complex. The approach taken here uses a plasmonic metamaterial absorber, which can exhibit near-perfect absorption within the desired spectrum with tunability [4].



(a)



(b)

Fig. 2. (a) The optical design of Microspectrometer-based gas sensor [3] (b) The thermopile arrays with absorption area

2. Absorber design

Since the mechanism of the metamaterial absorbers is based on the plasmonic or optical resonance, their absorption bandwidth is usually narrow. The approach to design the wide-band absorption is based on the use of four different sizes Al disk resonators in one unit cell. The corresponding absorption spectrum is about 95% with a ±4% ripple between 3 to 4 μm at normal incidence. The operation principle and the design of the metamaterial absorbers were presented before [5]. This paper investigates the challenges in the fabrication of the detector array together with the absorbers. Although, Au and Ag are more popular metals for use as the plasmonic materials in mid-IR metamaterial absorbers, these materials are poorly CMOS-compatible. Figure 3 shows the single peak absorption which is based on a magnetic plasmonic resonance for identical geometry and demonstrates that by an optimization of geometrical parameters, perfect absorption can be achieved using Al, despite the fact the material is less conductive and thus results in higher losses as compared to Au. A comparative study of the quality factor and bandwidth of the peaks obtained for the different metals in a certain geometry reveals that the smaller intraband loss ratio γ/ω_p of high-loss metals indeed results in stronger plasmonic resonance, smaller bandwidth, and higher selectivity. Therefore, the noble metals such as Au and Ag are the best options for narrowband absorption. Although Al has a smaller quality factor, due to its higher loss, wideband absorption spectra with significant out-of-band rejection can be achieved in the mid-IR.

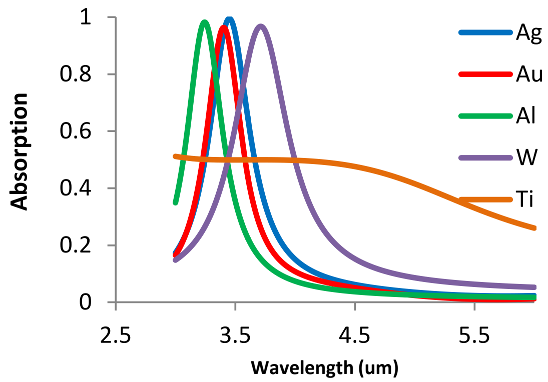


Fig. 3. Absorption peak for different metals with identical geometry

Wideband operation over the 3-4 µm spectral range is obtained by staggered tuning of four Al disk resonators in one $1.5 \times 1.5\ \mu m^2$ unit cell. Using four different values of the radius of the Al disk between 0.50 µm and 0.63 µm and a SiO_2 layer thickness of 150 nm (Fig. 4). Simulations reveal an average absorption of about 95% with a ±4% ripple at normal incidence, which reduces to about 80% absorption at 20^{o} incidence angle (Fig. 5). Also, the symmetrical geometry of the Al disks results in an almost polarization-independent sensitivity of the absorption band.

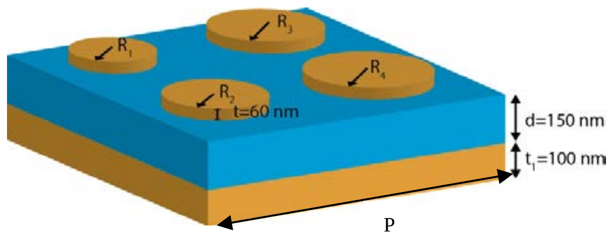


Fig. 4. The unit cell schematic of the multi-resonator absorber. Periodicity (p)=1.5 um. R1=500 nm, R2=530nm, R3=570 nm, R4=630 nm

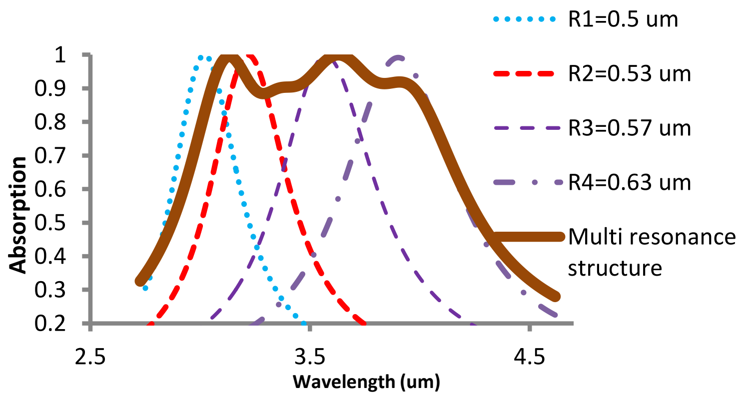


Fig. 5. Simulated absorption spectra of the multi-resonance absorber using FDTD method.

3. Fabrication Process

The detector array structure is based on an array of thermopiles that are fabricated on a SiN membrane to minimize the thermal mass of the detectors. A 2 µm thick TEOS layer is initially deposited used as the sacrificial layer under a 600 nm SiN layer.The thermopile arrays are then fabricated on the SiN layer. Figure 6 shows the SEM photo of several neighboring pixels.The absorber layer is fabricated on top of the thermopile elements.The fabrication flow for the absorber on top of the SiN membrane with the thermopile array using a lift-off process is schematically presented in Fig. 7. A 100 nm thick Al film is sputtered on the detector array. This layer acts as the metallic back plane. Subsequently, a 150 nm thick SiO_2 layer is deposited by Atomic Layer Deposition (ALD) on the Al layer for use as the dielectric layer of the metamaterial absorber. Afterwards, a layer of e-beam resist is spin-coated on the SiO_2 dielectric layer, and e-beam lithography (EBL) is used to define the patterns of the resonating structures. A lift-off process is considered for the pattern transfer from the resist layer into the top metal layer. After EBL exposure and development, an inverse pattern of the disks is made in the resist layer. Subsequently, the top aluminum layer is directly deposited on the patterned resist. The remaining resist layer, with the Al on top of it, are removed. The remaining structure layer has the desired metallic pattern. Finally, a set of openings is patterned and etched through the membrane and absorber layers. These access holes are used for the under-etching of the sacrificial TEOS layer and the drying of samples.

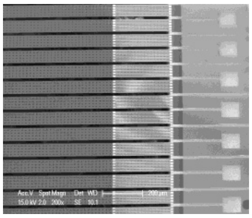


Fig. 6. The fabricated thermopile detector arrays without absorber.

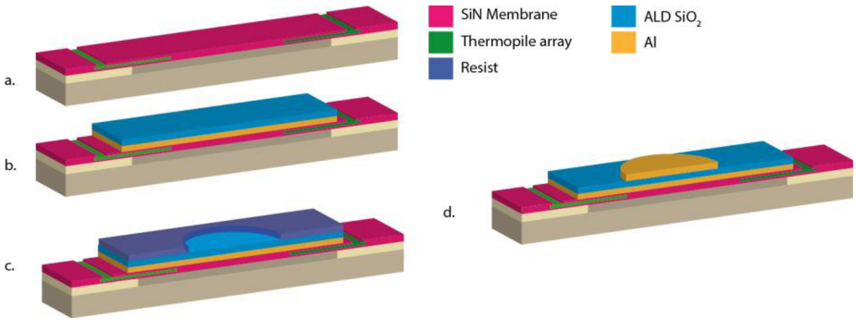


Fig. 7. The fabrication flow with lift-off process: a. Substrate with detector array (thermopile) on a 0.9 μm thick SiN membrane; b. Deposition and patterning of Al and SiO_2; c. Resist coating and e-beam lithography and development of patterns; d. Deposition of Al and lift-off.

4. Conclusion

The design of a detector array with metamaterial absorbers intended for the gas sensing application in the infrared is presented in this paper. While the specific advantage of the LVOF-based microspectrometers is the high-resolution spectral analysis over a relatively narrow band (as compared to grating-based systems), the out-of-band rejection is an important drawback.The generic tunability and spectral sharpness of the metamaterial absorbers make it a suitable candidate in the LVOF-based microspectrometers. Simulations indicate a 95±4 % absorption over the 3-4 μm spectral band using Al. The metamaterial absorber layer is realised on the thermopile arrays, and the sacrificial layer is then removed. The integration of the absorber layer and the free-standing thermopile array provides a sensitive and selective detector array. Future work is aiming at the spectral analysis of the fabricated absorber layers.

References

[1] B. H. Stuart, Infrared Spectroscopy, Fundamentals and Applications, Wiley, 2004.
[2] N. P. Ayerden, G. de Graaf, and R. F. Wolffenbuttel, Compact gas cell integrated with a linear variable optical filter, Optics Express vol. 24, pp. 2981-3002, 2016/02/08 2016.
[3] M. Ghaderi, N. P. Ayerden, A. Emadi, P. Enoksson, J. H. Correia, G. de Graaf, R. F. Wolffenbuttel, Design, fabrication and characterization of infrared LVOFs for measuring gas composition, Jounal of Micromechanics and Microengineering 24 (2014) 084001.
[4] Landy, N. Sajuyigbe, S. Mock, J. Smith, D. Padilla, W. ,Perfect Metamaterial Absorber. Phys. Rev. Lett. 2008, 100, 207402.
[5] E. Karimi Shahmarvandi, M. Ghaderi, N. P. Ayerden, G. de Graaf, R. F. Wolffenbuttel, CMOS-compatible metamaterial-based wideband mid-infrared absorber for microspectrometer applications, Proc. SPIE 9883, Metamaterials X, 988309 (April 18, 2016); doi:10.1117/12.2227800.