Resonance Cavity Enhanced Midinfrared Photodetectors Employing Subwavelength Grating

M. Zohar, M. Auslender, S. Hava
Ben-Gurion University of The Negev, Department of Electrical Engineering, 653 Beer Sheva 84105 Israel
L. Faraone
School of Electrical, Electronic and Computer Engineering, The University of Western Australia, Crawley 6009, Australia

***Abstract-* A new type of resonance cavity enhanced (RCE) photodetector is being proposed. The cavity in this structure includes a grating with nearly perfect retro-reflection as a front mirror and conventional multilayer structure as the back mirror.**

I. INTRODUCTION

It is well known that inserting a photosensitive or optically active medium into a Fabry-Perot (FP) cavity enhances detection efficiency as a result of multiple reflections between the cavity mirrors. In a high-Q FP cavity, up to 100% efficiency enhancement may be obtained if the round-trip phase, i.e. the phase difference between each succeeding reflection, satisfies the condition

$$\delta_0 \equiv \delta(\lambda_0) = 4\pi n_c(\lambda_0) t_c/\lambda_0 + \varphi_f(\lambda_0) + \varphi_b(\lambda_0) = 2\pi n \qquad (1)$$

Here λ_0 is a resonance wavelength n_c is the refraction index and t_c is the thickness of the spacer, φ_f and φ_r are the reflection phases of the mirrors and n is an integer.

In the last two decades, the science and technology of diverse RCE photonic devices, including RCE photodetector (PDs) [1], have been steadily maturated. High performance photodetectors and imagers in the mid-wave infrared (MWIR) range (3-10μm) are attracting increasing interest due to their wide applications in security surveillance, chemical sensing, and industrial processes monitoring [2, 3]. Currently, most MWIR detectors are built based on flat-surface mirrors, such as weakly transparent metal films, or specially designed dielectric multilayer, e.g. stack of quarter-wave pairs of the high/low (HL) index layers known as distributed Bragg reflector (DBR). The optical properties of the multilayer is elaborately explored subject, see e.g. [4]. For thermal PDs, the absorbed portion of incident radiation wholly determines the response, so the optical absorbance A is just the fair efficiency measure. The key figure for photodiode and photoconductor PDs is the quantum efficiency η defined as joint probability of that (i) an incident photon generates an electron-hole pair; (ii) the pair contributes to the detector current or voltage. For such PDs, $\eta = A$ only if the probability of (i)-(ii) equals unity for each absorbed photon.

The quantum efficiency of bulk PDs might be improved at the expense of increasing the absorbing layer's thickness t_a. However, using thicker absorbers results in the increase of thermal noise and transit times (in photodiodes). Since along with the high efficiency, high operation speed is crucial for the most of the PDs applications, it is desirable to improve η with

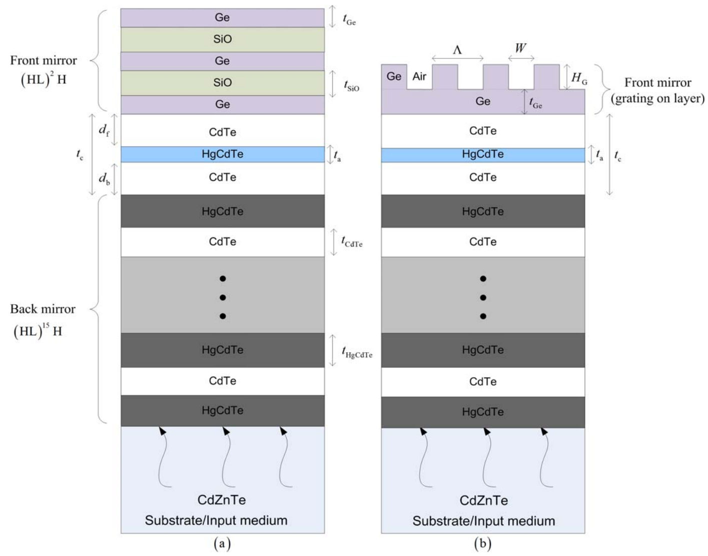

Fig. 1. Two RCE MCT-absorber structures with CdZnTe substrate and a quarter-wave stack $(HL)^m H$ ($H=Hg_{0.56}Cd_{0.44}Te$, L=CdTe) as the back mirror, thin $Hg_{0.71}Cd_{0.29}Te$ absorber layer. The front mirrors are: (a) quarter-wave stack $(HL)^k H$ (H=Ge, L=SiO) [12]; (b) Ge/air grating on a Ge layer.

-out the increase of t_a. In this work, the integration of sub-wavelength grating (SWG) structure which is poorly explored came in to picture; the SWG with the right design can perform as a dielectric micro-optical component with 100% resonant reflectance [5, 6], which can replace the less reflective DBR. In this paper we theoretically study the possibility of using SWG structures as the front mirrors in RCE PDs for MWIR on the base of mercury cadmium telluride (MCT) absorber.

II. ABSORBER DESIGN

A. Numerical Implementation

For the RCE MCT-absorber structures including a grating, we use a version of rigorous coupled wave analysis (RCWA) based on the in-layer S-matrix propagation algorithm (SMPA) [7]. Our SMPA is by-construction unconditionally numerically stable against increasing the grating grooves' depths, layers' thicknesses and extinction coefficients, and the truncation order.

For computations we employ MATLAB®, the native objects of which are vectors and matrices, and facilities crucial for coding RCWA comprise state-of-art linear algebra and optimization packages. High programming efficiency of smart codes, well developed graphics and elegant graphical user interface (GUI) builder are among the other reasons of using MATLAB®.

B. Modified RCE MCT Absorber Structure

The reported RCE MCT-absorber structure [8, 9] shown in Fig.1 (a) is of the usual type, i.e. the FP cavity embedding the $Hg_{0.71}Cd_{0.29}Te$ absorber layer has multilayer dielectric mirrors. The front mirror is $(HL)^kH$ Ge/SiO DBR (small extinction of SiO would have no effect at small k) and the back mirror is $(HL)^mH$ $Hg_{0.56}Cd_{0.44}Te$/CdTe DBR which is deposited layer-by-layer on a CdZnTe substrate by MBE. The HgCdTe/CdTe bi-layers provide good lattice matching for depositing the cavity and absorber layer but closeness of the refraction indexes of $Hg_{0.56}Cd_{0.44}Te$ and CdTe requires m=30 (~ 20μm thick DBR) to achieve desired reflectivity [10].

A modified RCE MCT-absorber structure, in which we replaced the front mirror by a one-dimensional dielectric grating, is shown in Fig.1 (b). The fabrication of such a grating supposedly amounts to two steps: depositing one Ge layer on the top of CdTe cavity layer and etching grooves in the layer until some depth H_G, through periodic mask with a period Λ and window W. We implemented the optimization program to receive numerous modified RCE MCT-absorber structures for TE, TM and TEM polarizations with six degrees of freedom. We aim at ~100% A for all the TE, TM and TEM-polarized structures, the structure obtained in this paper is a TM-polarized structure. The optimization for λ_0 = 4.415μm yielded the following results: t_{Ge} = 0.628μm, H_G = 0.921μm, d_b = 0.260μm, d_f = 0.504μm, Λ=1.456μm, W/Λ=0.660. The absorber (t_a = 0.075μm), cavity and back mirror are similar to those of the structure in Fig.1 (a).

III. Results

Fig. 2 shows the TM-polarized zero-order reflection (back to the CdTe half-space) efficiency R_0 from the stand-alone grating mirror of the TM polarization-selective RCE MCT-absorber structures. The spectra exemplify the optimization intended to maximize R_0 in a range around λ_0.

The A spectra of the structure are also displayed in Fig. 2 and exemplify the optimization intended to maximize A at λ_0, with nearly 100% peak efficiency. We would like to note that the A spectra achieved for TE polarization are quite similar.

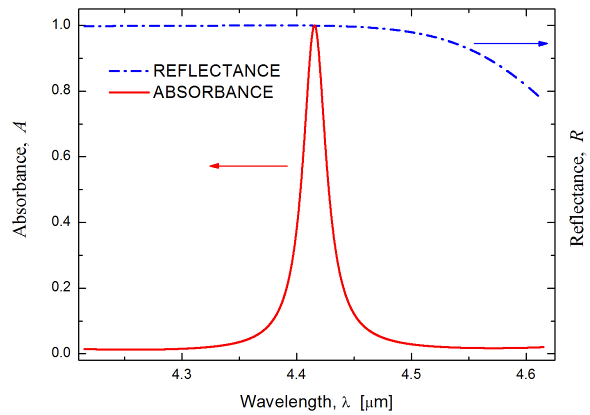

Fig. 2. The polarized absorbance spectra of the designed polarization-selective RCE MCT-absorber structure; the zero-order reflection (back to the CdTe half-space) efficiency from the stand-alone grating mirrors of the polarization-selective RCE MCT-absorber structure.

IV. Discussion And Conclusion

Increasing the efficiency of RCE MCT-PDs by using the Ge/SiO DBR front mirror with more bi-layers, or a metallic mirror [11, 12] seems hardly feasible because of absorption losses. A new dielectric FP cavity in which the front mirror is a grating structure with perfect retro-reflection was proposed. The design and analysis of the RCE MCT-absorber structures with the new resonance cavity were carried out. It was conclusively shown that one can design the modified RCE MCT-absorber structures to outperform the conventional ones for the linearly polarized radiation. Besides shrinking the front mirror, these designs allow to notably reduce the back DBR mirror, thus reducing the overall size of the RCE device, without deteriorating its efficiency. We also designed the RCE-TEM structure for a nearly 100% efficiency operation under unpolarized irradiation, though in this case the designed grating dimensions should be strictly followed.

References

[1] M. S. Unlu and S. Strite, "Resonant cavity enhanced photonic devices," *J. Appl. Phys.*, vol. 78, pp.607-639, Jul 1995.

[2] J. Wang, J. Hu, P. Becla, A. M. Agarwal, and L. C. Kimerling "Resonant-cavity-enhanced mid-infrared photodetector on a silicon platform," *Opt. Express.*, vol. 18, pp. 12890-12896, Jun 2010.

[3] A. Rogalski, J. Antoszewski, and L. Faraone, "Third-generation infrared photodetector arrays," *J. Appl. Phys.*, vol. 105, pp. 091101-091144, May 2009.

[4] O. S. Heavens, Optical Properties of Thin Solid Films (Reprint), Dover Publ., New York 1991.

[5] S. S. Wang and R. Magnusson, "Theory and applications of guided-mode resonance filters," *Appl. Opt.* vol. 32, pp. 2606-2613, May 1993.

[6] C.F.R. Mateus and M.C.Y. Huang and L. Chen and C.J. Chang-Hasnain and Y. Suzuki "Broad-band mirror (1.12-1.62 μm) using a subwavelength grating," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1676 1678, July 2004.

[7] M. Auslender and S. Hava, "Scattering-matrix propagation algorithm in full-vectorial optics of multilayer grating structures," *Opt. Lett.* vol. 21, pp. 1765-1767, Nov. 1996.

[8] J. G. A. Wehner, C. A. Musca, R. H. Sewell, J. M. Dell, and L. Faraone, "Mercury cadmium telluride resonant-cavity-enhanced photoconductive infrared detectors," *Appl. Phys. Lett.* Vol. 87, p. 211104, Nov. 2005.

[9] J. G. A. Wehner, C. A. Musca, R. H. Sewell, J. M. Dell, and L. Faraone, "Responsivity and lifetime of resonant-cavity-enhanced HgCdTe detectors," *Solid-State Electron.,* vol. 50, pp. 1640-1648, Sep. 2006.

[10] J. G. A. Wehner, R. H. Sewell, J. Antoszewski, C. A. Musca, J. M. Dell, and L. Faraone, "Mercury cadmium telluride/cadmium telluride distributed Bragg refctors for use with resonant cavity-enhanced detectors," *J. Electron. Mater.*, vol. 34, pp. 710-715, Jan. 2005.

[11] C.-H. Chen, K. Tetz and Y. Fainman, "Resonant-cavity-enhanced p-i-n photodiode with a broad quantum-efficiency spectrum by use of an anomalous dispersion mirror," *Appl. Opt.*, vol. 44, pp. 6131-6140, Oct 2005.

[12] J. Kaniewski, J. Muszalski and J. Piotrowski, "Resonant microcavity enhanced infrared photodetectors," *Optica Applicata,* vol. 37, pp. 405-413, May 2007.