High Sensitivity Photodetectors based on Nanometer Scaled Periodic Multilayered Structures

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Abstract- We propose and design high efficiency thin Photodetectors (PDs), using micro-cell gratings, which enable near-field enhanced (NFE) mid IR absorption by confining the EM fields to the absorber region. These PD types have a different operation principle as compared to the conventional PDs they replace.

I. INTRODUCTION

Photodetectors (PDs) are indispensable components in optical sensors, communication systems and photonic interconnects. For most applications, a high signal-to-noise ratio and operation speed concurrent with a high quantum efficiency η, are crucial. To achieve a drastic decrease in an absorber's thickness ta, while keeping high η, the impinging light needs to be strongly confined in the vicinity of the absorber. One of the means for this confinement is a solid-state resonant Fabry-Perot (FP) cavity. Resonant cavity enhanced (RCE) PD [1], with a much thinner absorber, enables greater efficiency and faster light detection and higher operating temperatures than the monolithic PD. 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.

The integration of the sub-wavelength grating (SWG) structure, which is almost unexplored, came into focus. The SWG with a smart design can perform as a dielectric micro-optical component with a 100% resonant reflectance [2, 3], which can replace the less reflective distributed Bragg reflector (DBR).

As a first step to thinner RCE PDs, we propose to replace one DBR by a grating-on-layer (GL) mirror [4, 5]. However, since no further thinning is possible due to thickness limitation inherent to the RCE devices, another mechanism for enhancing light-matter interaction is needed. A promising solution is resonant electromagnetic (EM) field recirculation in micro/nanocavities, which confines light to the micro/nanoscale volumes [6, 7]. Here we propose and design the thinnest high efficiency PDs, using the micro-cell gratings, to enable near-field enhanced (NFE) mid IR absorption by confining the EM fields to the absorber region. In these PDs the cavity-absorber sandwich is structurally the same as in RCEs, but these PD types are different in principle from the conventional DBRs they came to replace.

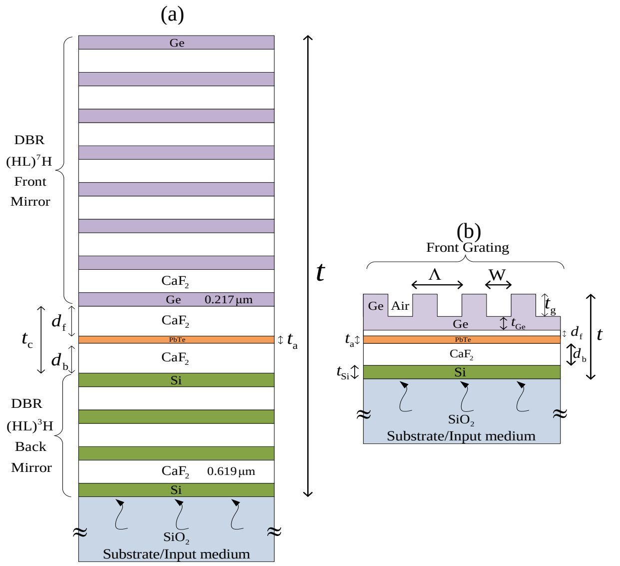

Fig. 1. The resonantly enhanced optical absorption structures: (a) conventional RCE and (b) NFE PD.

II. STRUCTURE DESIGN

A. Numerical Implementation

For the ultrathin PbTe-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) [8]. Our SMPA is a by-construction unconditionally numerically stable against increasing the grating grooves' depths, layers' thicknesses, extinction coefficients and the truncation order.

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

B. Ultrathin Detector Structure Design

Structure shown in Fig.1 (a) is of the usual RCE type, i.e. the FP cavity, embedding the PbTe absorber layer, has

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multilayer dielectric mirrors. The front mirror is $(HL)^kH$ Ge/CaF$_2$ DBR and the back mirror is $(HL)^mH$ Si/CaF$_2$ DBR which is deposited layer-by-layer on a SiO$_2$ substrate. Similar structure with the same absorber material but different cavity and multilayer materials have been reported [9].

An ultrathin PbTe-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 CaF$_2$ cavity layer and etching grooves in the layer to a desired depth t_g, through a periodic mask with a period Λ and window W. We implemented the optimization program to receive numerous ultrathin PbTe-absorber structures for TE, TM and TEM polarizations with six degrees of freedom. We aim at ~100% efficiency η for all the TE, TM and TEM-polarized structures. The structure we present in this paper is a TEM-polarized structure. The optimization for λ_0 = 3.5 μm yielded the following results: t_{Ge} = 0.28 μm, t_g = 0.55 μm, d_b = 0.35 μm, d_f = 0.05 μm, Λ=1.57 μm, W =1.1 μm. The absorber layer thickness t_a = 0.1 μm was the same for both structures shown in Fig.1.

III. RESULTS

Fig. 1 presents schematics of two PbTe based on mid IR PDs. Fig. 1(a) shows the conventional RCE PD serving as a reference, in which Ge/CaF$_2$ and Si/CaF$_2$ stacks compose the front and back mirrors, respectively, CaF$_2$ wraps the absorber and SiO$_2$ is the substrate. Fig. 1(b) shows a proposed NFE PD in which the substrate, absorber and its cavity-like ambient and irradiation mode are the same as in Fig. 1(a), however the front and back mirrors are replaced by a Ge/Ge-air GL and a Si quarter-wavelength thick layer, respectively. The micron-scale grating period Λ, groove width W and etch depth t_g, as well as the submicron thicknesses t_{Ge}, d_f and d_b of the Ge, front and back cavity layers, respectively, were the optimization variables. Fig. 2 shows the absorption spectra of the RCE and the NFE structures. Here it is seen that the absorption spectrum of the RCE structure is narrow, and the NFE structure exhibit larger spectral bandwidth.

The NFE structures notably outperform the optimized RCE in the peak efficiency (η_{max} of 89.92%), being 8 times thinner with η_{max} of 98.56% for a selected unpolarized NFE structure. The strong local resonant electric-field enhancement seen in Fig. 3 visualizes the suggested EM confinement at the resonant wavelength λ_0=3.5 μm and correlates fairly with nearly perfect performance of the designed ultrathin PDs.

IV. DISCUSSION AND CONCLUSION

We have showed the theoretical feasibility of subwavelength thick PDs based on the NFE optical absorption, which bypass a lower thickness bound inherent to RCE PDs, both conventional [1] and those implemented with a GL mirror [4,5]. NFE PDs being ~1.6 μm thick, show a nearly 100% peak efficiency unattainable by conventional RCE PDs. The proposed NFE PDs may potentially be useful in integrated high capability multi-detector arrays, in which highly efficient ultrathin PD elements are vital.

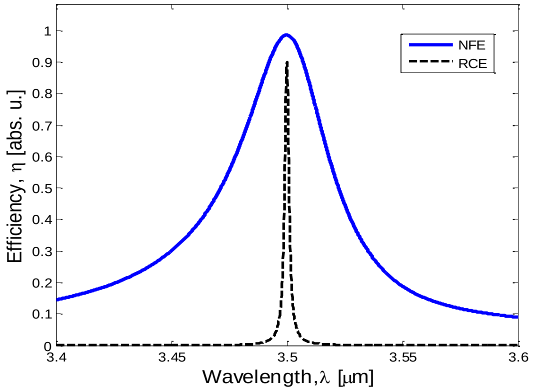

Fig. 2. Efficiency spectra at normal incidence of the structure presented in Fig. 1. (b) and described in the text.

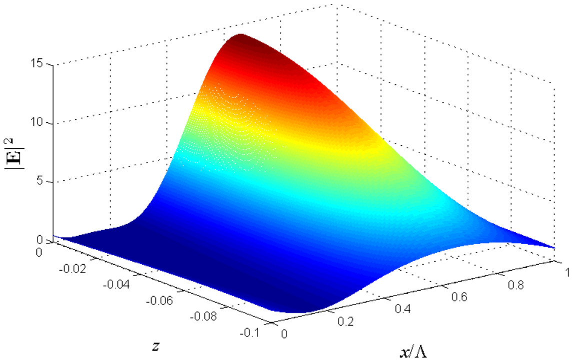

Fig 3. The electric-field amplitude squared (normalized to that in the incident wave) across the absorber ($0 \geq z \geq -t_a$) in the designed NFE structure; the in-depth coordinate z is in microns, and the lateral one x is normalized to the grating period.

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