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Electromagnetic modeling and resonant detectors and arrays

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HIGHLIGHTS

- Developed an electromagnetic model to calculate quantum efficiency quantitatively.
- Design an efficient photon trap, and observed QE as high as 71%.
- Demonstrated the R-QWIP in FPAs and achieved QE in the range of 30–40%.
- Designed detectors for gas sensing, high-speed detection, and dual-band detection.

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ABSTRACT

We recently developed a finite element three-dimensional electromagnetic model for quantum efficiency (QE) computation. It is applicable to any arbitrary detector geometry and materials. Using this model, we can accurately account for the open literature experimental results that we have investigated, which include those from GaAs solar cells, GaSb type-II superlattices, and GaAs quantum wells. We applied the model to design a photon trap to increase detector QE. By accumulating and storing incident light in the resonator-QWIP structure, we observed experimental QE as high as 71%. This improvement shows that we are now able to fully determine the optical properties of QWIPs. For example, we can design QWIPs to detect at certain wavelengths with certain bandwidths. To illustrate this capability, we designed QWIPs with its QE spectrum matching well with the transmission spectrum of a medium. We subsequently produced several focal plane arrays according to these designs with 640 × 512 and 1 K × 1 K formats. In this paper, we will compare the modeled QE and the experimental results obtained from single detectors as well as FPAs.

1. Introduction

In the past, achieving a high quantum efficiency (QE) in infrared detection requires a thick material and a large absorption coefficient α. This requirement limited severely the choice of materials when the detection wavelength is longer than 8 μm. If a high QE can be obtained even with a thin layer and a small α, it will open up many more possibilities. Materials that are once regarded as problematic, such as those with small α, short minority carrier diffusion length, or small critical growth thickness, can now be considered. To realize this possibility, we propose a detector structure that can trap and store incident light until the light is absorbed. With a perfect trap, the QE will no longer be limited by the material thickness or α. To make an effective trap, the light must not transmit out of the detector when it hits the detector boundaries, and it must not interfere destructively with the incident light or other light already present in the detector. In this work, we will describe one of such designs that we call the resonator-X, or R-X, where X stands for any detector materials [1,2].

2. Electromagnetic modeling

To understand the proposed detector, let's consider a detector slab in Fig. 1(a) with metal on top, and light is incident from the bottom substrate. With this detector geometry, the light will bounce up and down between the metal and the substrate/air interface, with which a Fabry–Perot etalon (FBE) is formed. However, this FBE does not confine photons effectively because the substrate transmission can be large and because optical interference can either aid or suppress the escape of light at the interface, resulting in QE oscillations that are centered about its classical value. If the detector top surface contains certain roughness instead as shown in Fig. 1(b), the light will be diffracted at an angle. And if this angle is larger than the critical angle at the substrate/air interface (~18° for GaAs), the light will be totally

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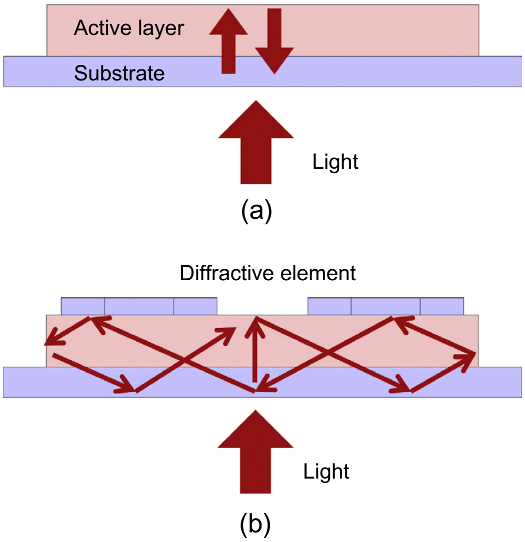

Fig. 1. (a) In conventional detectors, incident light travels up and down the material slab, creating FB oscillations. In resonant detectors, light circulates inside each pixel, making the pathlength longer.

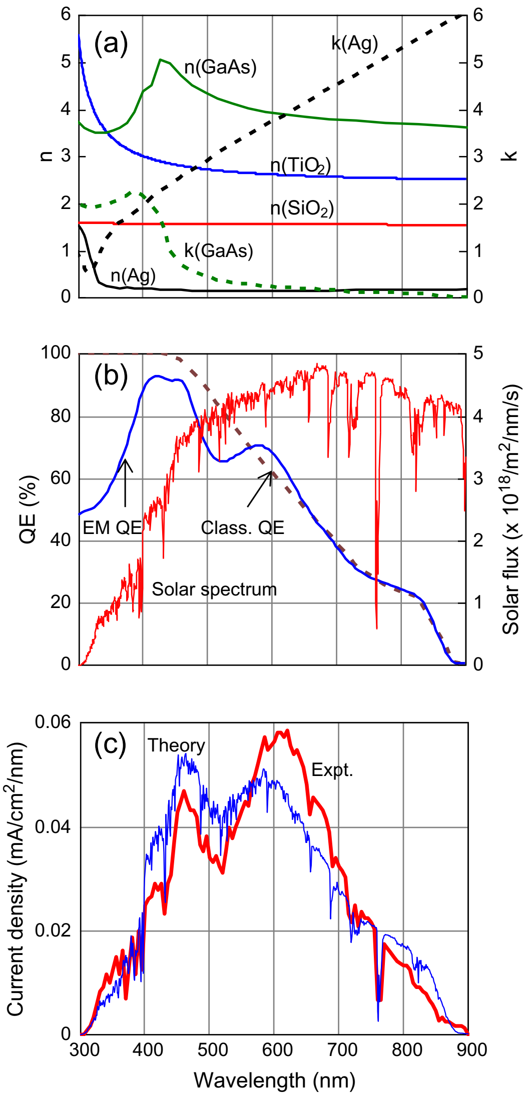

Fig. 2. (a) The refractive indices of the optical materials used in the multilayer solar cell. (b) The calculated classical and EM QE of the solar cell and the solar flux under 1-sun illumination. (c) The calculated and measured photocurrent spectra. They agree well without any fitting parameters. The experimental peaks at 460 and 600 nm, which are absent in the classical model, are predicted by the EM modeling.

internally reflected at the substrate and will stay inside the detector. When the same is also true for all other detector sidewalls, the light will be totally confined. To account for interference effects, the size and shape of the detector volume must be adjusted such that the scattered optical paths form a constructive interference pattern inside the detector. Under this condition, the newly incident light will be able to reinforce the light already under circulation, and the optical energy can be accumulated and stored in the detector as in a resonator. Therefore, by designing the detector into a resonator with a diffractive surface, i.e. an R-X structure, an effective photon trap can be obtained.

To design an efficient R-X detector, we need to calculate accurately the electromagnetic (EM) field distribution inside the detector under normal incident condition. With this distribution, the QE, labeled η, can be obtained through the following equation [1–3]:

$$\eta = \frac{n\alpha}{AE_0^2}\int_V |E(\vec{r})|^2 d^3r\,, \tag{1}$$

where n is the material refractive index of the detector material, α is the absorption coefficient, A is the detector area, E_0 is the incident electric field incident from the air, V is the detector active volume, E is the self-consistent total electric field. In this work, we adopted a finite-element method (FEM) to calculate the field quantities using a commercial EM solver. For a complete set of modeling instructions, please refer to Ref. [1,2].

3. Verification of the em model

Before we use FEM to calculate the QE of R-X detectors, we apply it to the existing experiments in open literature to confirm its validity. The first example is a multi-layer solar cell studied by Grandidier et al. [4]. In their device, a 100-nm thick GaAs layer is used for the active material. It is sandwiched between an optical reflector (50 nm of Ag) and a composite anti-reflection coating (40 nm of TiO_2 and 90 nm SiO_2). The optical properties of these layered materials found in open literature are displayed in Fig. 2(a).

Based on the refractive indices of the material layers, the value of α and thus the EM QE of the solar cell under normal incidence can be computed and it shown in Fig. 2(b). Several peaks appear in the spectrum, and they are at 420, 460, 590, and 820 nm. To check the modeled result, we also calculated the classical QE based on the ray-tracing technique assuming two passes of light and 100% substrate transmission. The result is also shown in Fig. 2(b) as dashed curve. The two theoretical curves generally agree with each other except near the main peaks. Based on the modeled QE and the solar flux of 1-sun, the photocurrent density (J_{photo}) can be predicted, and it is shown in Fig. 2(c). Both the calculated spectral lineshape and the absolute magnitude match well with the measured spectrum. Furthermore, the total generated photocurrent was measured to be 16.38 mA/cm^2, while the theoretical integrated photocurrent is 16.51 mA/cm^2. Without knowing the actual properties of the material layers, the present agreement is deemed to be satisfactory.

In the infrared regime, Huang et al. [5] observed pronounced Fabry–Perot oscillations in their dual-band type-II superlattice detector. The broadband nature of this detector is particularly suitable for the study of FBEs. The detector contains two stacks of active materials, a "blue" stack and a "red" stack, with different cutoff wavelengths. Each stack is 2-µm thick and the total detector