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ScienceDirect

Infrared Physics & Technology 49 (2007) 183–186

INFRARED PHYSICS & TECHNOLOGY

www.elsevier.com/locate/infrared

Narrow spectral band monolithic lead-chalcogenide-on-Si mid-IR photodetectors

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Available online 26 July 2006

Abstract

Narrow spectral band infrared detectors are required for multispectral infrared imaging. We review the first photovoltaic resonant cavity enhanced detectors (RCED) for the mid-IR range. The lead-chalcogenide (PbEuSe) photodetector is placed as a very thin layer inside an optical cavity. At least one side is terminated with an epitaxial Bragg mirror (consisting of quarter wavelength PbEuSe/BaF_2 pairs), while the second mirror may be a metal. Linewidths are as narrow as 37 nm at a peak wavelength of 4400 nm, and peak quantum efficiencies up to above 50% are obtained.

Keywords: Resonant cavity; Infrared sensors; Lead-chalcogenides; Bragg mirrors; Molecular beam epitaxy

1. Introduction

The most sensitive detectors for the mid-infrared range (3–20 μm) are obtained with narrow gap semiconductors (NGS) [1,2]. These detectors have a broad spectral sensitivity up to the cut-off wavelength which is determined by the (narrow) band gap. The quantum efficiency is high due to the direct band gap. Large focal plane arrays (FPAs) in one or two dimensions are fabricated for various applications. Preferred materials are HgCdTe and InSb. The IR-FPAs are typically fabricated in a hybrid structure: A NGS-chip containing the IR-sensors is mated to the Si-read-out chip with In-bumps. Narrow gap lead-chalcogenides (PbSnX, PbEuX, X = Se, Te) may be applied, too, for this purpose, but not many groups are presently working on this topic. Here, Si-substrates are used onto which the lead-chalcogenide is grown by molecular beam epitaxy (MBE). This is possible despite the huge lattice- and thermal expansion mismatch. Photovoltaic lead-chalcogenide sensors are rather tolerant to structural defects (in contrast to the HgCdTe or InSb material families). Lead-chalcogenide IR-arrays have been fabricated with cut-off wavelengths ranging from 3 to 12 μm [2]. The Si-substrate may even contain the read-out electronics: A two dimensional monolithic array with 96×128 pixels for the 3–5 μm range has been realized [3].

In addition to single color IR-FPAs, multispectral or even hyperspectral sensor arrays for enhanced object discrimination operating in different bands and/or narrow lines are needed today [4].

Preferably, the detector array itself is able to discriminate the spectral ranges rather than to employ passive filters in front of the array. The spectral bands or narrow lines should preferentially be tunable, depending on the application.

Here, we describe narrow spectral band infrared detectors based on monolithic resonant cavities which exhibit sensitivity in a very narrow spectral band only. For the first time, high quantum efficiencies and single narrow line widths have been obtained in the mid-IR range [5].

They are realized with epitaxial narrow gap lead-chalcogenide layers which are especially suited for this purpose:

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1350-4495/$ - see front matter
doi:10.1016/j.infrared.2006.06.001

(1) Cut-off wavelengths between 3 μm and >15 μm are obtained by chemical tuning [2,3].
(2) Distributed Bragg reflectors (DBR) with high reflectivities are easily obtained with only a few $\lambda/4$ quarter wavelengths layer pairs with alternating high (H) and low (L) refractive indices. Typical combinations are PbEuSe/EuSe [6] or PbEuSe/BaF_2 [7]. This is because the refractive index of the H layer (PbEuSe) is as high as $n_H \cong 5$, while that of the L layers are low ($n_L = 2.4$ for EuSe, $n_L = 1.43$ for BaF_2). With such large H/L contrasts, one to three H/L pairs already give high reflectivities.
(3) Lead-chalcogenide materials are "forgiving", IR-devices with sufficient quality result even in materials containing a considerable number of dislocations. This allows lattice-mismatched growth by molecular beam epitaxy even on Si-substrates.
(4) Pb/PbXSe ($X = Eu, Sn$) metal/semiconductor contacts yield high quality photovoltaic IV–VI detectors. Whole large focal plane arrays even on active Si-chips containing read-out electronics have been fabricated with this technology [3].

2. RCED principle

As shown in Fig. 1, resonant cavity enhanced detectors (RCEDs) consist of a Fabry-Perot cavity with front and back end terminated by high reflectivity mirrors [8]. At the cavity resonance wavelengths, photons enter the cavity and may cycle back and forth many times before they are absorbed in the detector (absorber) layer. The optical length of the cavity determines the resonance wavelengths, and the finesse the widths of the resonances. If the front and back mirrors have high reflectivities and the absorption inside the cavity is low, the finesse is high and therefore a very narrow line width is obtained. High quantum efficiencies result even for very thin absorber layers in this case because of the photon cycling effect. In addition, the thin detector layer may result in a much lower noise than in non-cavity broad band detectors since the absorption thickness and therefore the detector volume is small, leading to lower generation-recombination noise.

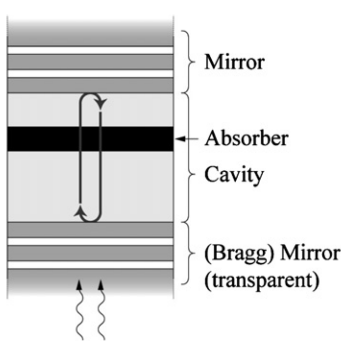

Fig. 1. Principle of a RCED.

3. Design and fabrication

The light enters through the bottom DBR which consists just of two pairs of $Pb_{1-x}Eu_xSe/BaF_2$ layers (Fig. 2). This mirror is nonabsorbing at the design wavelength (4.4 μm). It is followed by a nonabsorbing $Pb_{1-x}Eu_xSe$ spacer layer and the thin absorbing $Pb_{1-y}Eu_ySe$ ($y < x$) detector layer. The 5th order resonance was chosen for the present design. The top mirror consists of Pb which in addition forms the photovoltaic detector with the absorber layer. The thickness of this $Pb_{1-y}Eu_ySe$ absorber/detector layer is chosen in a way that it extends to near an antinode of the standing wave inside the cavity, therefore leading to high quantum efficiency.

The calculated reflectivities are 95% for the DBR and 98% for the Pb mirror. The latter was obtained by fitting reflection spectra, since tabulated reflectivities of Pb are not reliable and depend on the layer preparation and history.

The layers are grown on a Si(111) substrate in a two-chamber MBE system as described elsewhere [3]. A thin (2 nm) CaF_2 buffer is grown first on the Si-substrate for compatibility. The right part of Fig. 2 shows a cleaved cross section of the structure.

4. Device with 4.4 μm peak wavelength

The measured spectral response of the device described above is shown in Fig. 3. The linewidth is as narrow

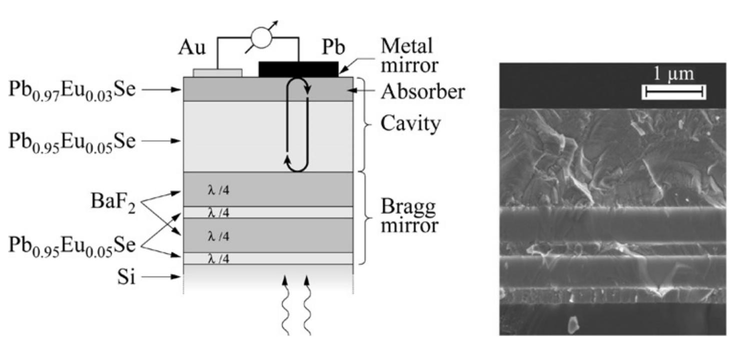

Fig. 2. Schematic cross section of a lead-chalcogenide RCED and corresponding scanning electron microscopic image.