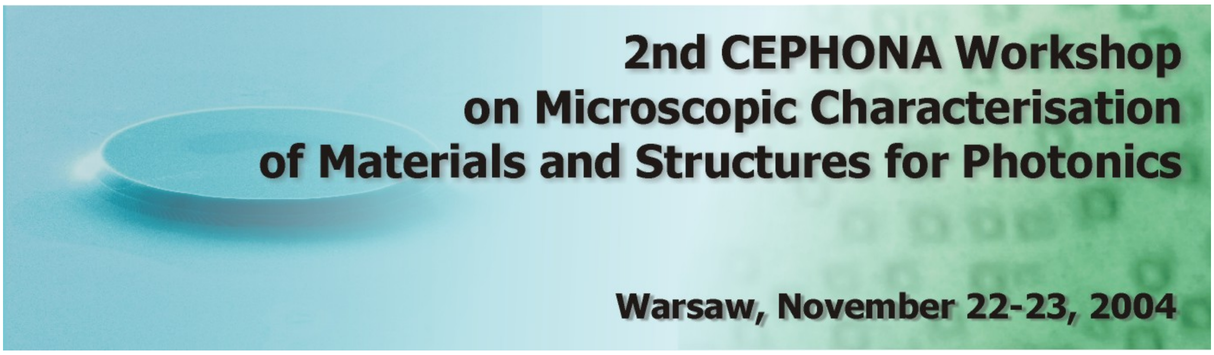

RESONANT-CAVITY ENHANCED PHOTO-DETECTORS

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ABSTRACT

Resonant-Cavity Enhanced Photo-Detectors (RCE-PD) are a very interesting class of the semiconductor devices. They consist from a thin absorption layer enclosed by two mirrors i.e., by one dimensional Fabry-Perot cavity. Those devices permit to achieve simultaneously high quantum efficiency and high bandwidth. The goal of this paper is to present the RCE-PD and most of all the influence of a cavity for quantum efficiency. The general rules of the design of RCE-PD and its performance are discussed.

1. INTRODUCTION

A conventional semiconductor *p-i-n* photo-detector consists from a thick absorption layer introduced in between additional layers which serves as contact layers or the barriers witch prevent the carrier escape. In order to make absorption process efficient i.e., achieve high quantum efficiency which is defined by the ratio of the number of electron –hole pairs to the number of photons the absorption layer has to be thick. The *rule of thumbs* is that the thickness of the layer should be at least two times grater then the wavelength for which the photo-detector is dedicated. Such thickness allows for efficient electron –hole generation (Fig. 1a) but in expanse of the bandwidth. The bandwidth is the measure of how fast a photo-detector responds to the series of light pulses. It is proportional to the carrier transition time from the place where electron-hole pairs are generated to the contacts layers. Thick layer increases the transition time decreasing the bandwidth of photo-detectors what, in turn, limits the number of photo-detector application. The way to over come the high quantum efficiency – high bandwidth contradiction is to make the multiple pass of the light through the absorption layer hence achieve high absorption on a thinner layer.

As an introduction the optical parameters of a PD of the conventional design are presented In the Fig. 1 there along the schema of the device the spatial distribution of the refractive index is shown. The device designed for 1550 nm bound consist from a 3100nm thick undoped InGaAs absorption layer sandwiched in between thin p- and n-type InAlAs contact layers, all epitaxialy grown on InP substrate. The differences in the refractive index between different layers influences the performance of the device. It is especially pronounced in case of elevated number of layers of different composition this will be shown further on. In case of this simple photo-detector the high index step between the vacuum/air (n=1) and semiconductor layer (n≅3.5) influences at most the device performance. It results in partial reflection of the light on the PD surface limiting the light penetration into the absorbing layer in consequence decreasing the quantum efficiency. In order to overcome this on the device surface the special antireflection coating is deposited. This is done in a separated step during the device fabrication procedure. Here Si_3N_4 is used which refractive index value n=1.88 is in between

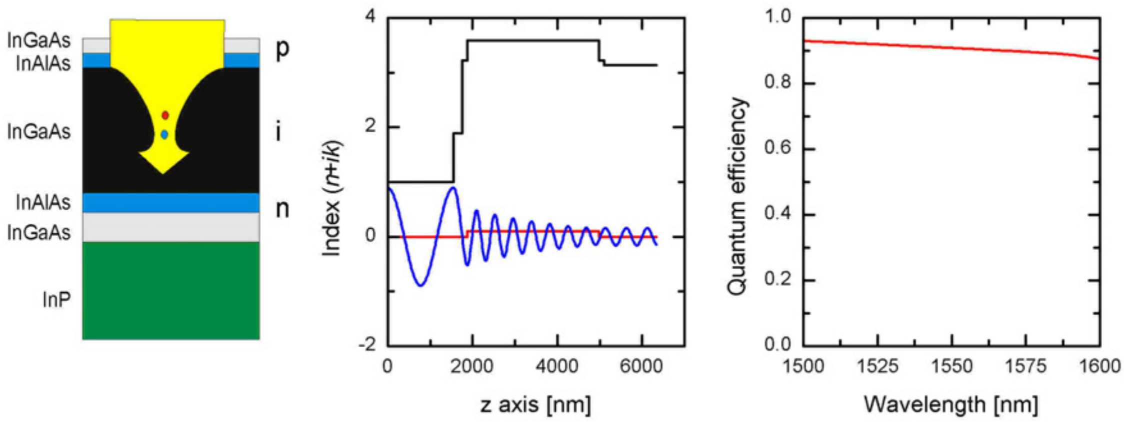

Fig. 1. A conventional photo-detector: schema of the epitaxial heterostructure light is introduced from the epi-side (a), spatial distribution of refractive index and the light wave penetration inside the heterostructure (b), the quantum efficiency spectrum (c).

those of air/vacuum and semiconductor and when its thickness correspond to the $\lambda/4n_{SiN}$ the reflectivity on the device surface can be decreased from over 0.2 to just as little as 0.01. This al all other data has been calculated using the transfer matrix methods [1]. Here the *rule of thumb* was applied and the absorption layer thickness equal to 3100nm (2*1550nm) allows for the quantum efficiency η=0.9. The high η value is achieved in expense of bandwidth. However the valuable feature of this conventional PDs is it flat spectral characteristic (Fig. 1c) what make such PD indispensable in many application.

2. SINGLE MIRROR PHOTO-DETECTORS

Nowadays almost all photonic devices are fabricated by epitaxial techniques Molecular Beam Epitaxy (MBE) or alternative Metal Organic Chemical Vapour Deposition (MOCVD). Both technology allows for the growth of layers with unprecedented thickness control, with well controlled composition and abrupt interfaces. By playing with the layer composition the layer optical parameters as bandgap i.e., the absorption edge or refractive index can be in wide range adjusted to the actual needs. The only constrain is the lattice constant since all the layers have to be lattice matched within the certain precision otherwise the accumulated strain will relax by the dislocation formation deteriorating the device performance. By MBE or MOCVD in a single epitaxial run a complete PD heterostructure can be fabricated. Such heterostructure consist along absorption layer from a number of additional ones which are required, for instance, to form contacts, to stop carrier diffusion etc. (Fig. 1a). By epitaxy also the mirrors can be easily integrated with the active region (Fig. 2a). The epitaxial mirrors are the Distributed Bragg Reflectors (DBR). DBR consists from a stack of the alternating layers of high and low refractive index. The thickness of those layers corresponds to the quarter of the wavelength of the light in the layer ($d=\lambda/4n$) for which the DBR is dedicated. The interferences of the light waves reflected on each interface result in very high reflection of the stack. The reflection increases with the number of the layers and the refractive index contrast. In case of the DBR consisting from GaAs/AlAs layers the reflection equal to those of silver surface is achieved for 10 pairs. It can be further increased exciding even the 0.998 when more high/low index layer pairs are employed. There is however a substantial difference between the DBR and the conventional metallic mirrors e.g., silver surface. The metallic mirrors have high reflection in very broad spectral range whereas the DBR shows high reflectivity only in the so called *stop band* usually few dozens of nanometres.

In the Fig. 2 there is shown the schema of a PD heterostructure employing a DBR. This photo-detector is designed for the operation in 1550nm range. It consists from a stack of the high InGaAs, (n_{InGaAs}= 3.59) and low InAlAs (n_{InAlAs}= 3.22) index layers functioning as the DBR mirror. The thicknesses of the layers are 108 and 120.4nm respectively what corresponds to the quarter of the wavelength in those materials (1550nm/4n). Those layers are heavily n-type doped with silicon. This

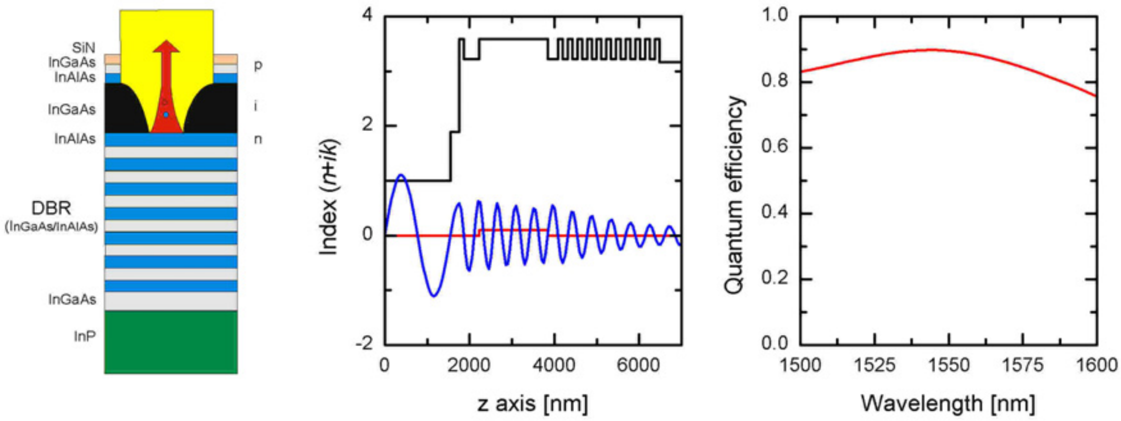

Fig. 2. A photo-detector employing a single DBR mirror schema of epitaxial heterostructure light is introduced from the epi-side (a), spatial distribution of refraction index (b), spectral response of the PD (c).

due to Moss effect shifts the absorption edge of InGaAs to higher energy making all the DBR layers transparent at 1550nm. On top of the DBR the 1296nm thick undoped InGaAs absorption layer along with p-type InAlAs barrier and InGaAs contact layer is designed. All heterostructure semiconductor layers are to be grown on and lattice matched to InP substrate. During the device fabrication surface of the device is antireflection coated. Such composition of the heterostructures results in high quantum efficiency similar to that of PD of the conventional construction (compare Fig. 1) but for a much thinner absorption layer, hence much greater bandwidth can be expected. This high quantum efficiency is achieved because light passes twice the absorption region. The single pass absorption is here only 0.65.

In case of the discussed PD the absorption layer thickness corresponds to the integer number of the half wavelengths (6λ/2n). This is a requirements which has to be fulfilled in order to make a non-destructive interference between light waves propagating in the layer incoming one and that reflected by DBR.

3. RESONANT-CAVITY ENHANCED PHOTO-DETECTORS

It has been shown that application of the single mirror in PD heterostructure i.e., making the light to pass twice the absorption region allowed to strongly decrease the absorption layer thickness. Further improve can be achieved when second mirror is used. Enclosing the absorption layer by two mirrors results in multiple passes of the light through the absorption layer thus increase of total light absorption even when the single pass absorption is strongly decreased.

The two mirror separated by a slab form an one dimensional optical cavity – Fabry-Perot resonator. In case of modern semiconductor technology usually the size of the cavity is comparable with the light wavelength. However the term microcavity is used only for the cavities for which there is only one resonance in the range of interest [2]. The physic of optical cavities is well review [1,3,4]. Here only the main features will be remained.

The light aim at the transparent slab enclosed by two reflecting or semi reflecting surfaces is reflected in total spectral range but the light of the resonant wavelength. This is because the light which passes through the front mirror and penetrate the slab undergoes multiple reflection on both front and back side mirrors and due to interferences vanish at the wavelengths do not matching the resonance. Resonance is for the wavelength for which the slab thickness corresponds to integer number of half wavelength. At this wavelength a standing wave is form inside the slab with the amplitude much greater than those of incoming wave. The features of the cavity depends on the thickness (*L*) and refractive index (*n*) of the slab and mirror reflectivity r_1 and r_2 and is commonly described by finesse:

$$F = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

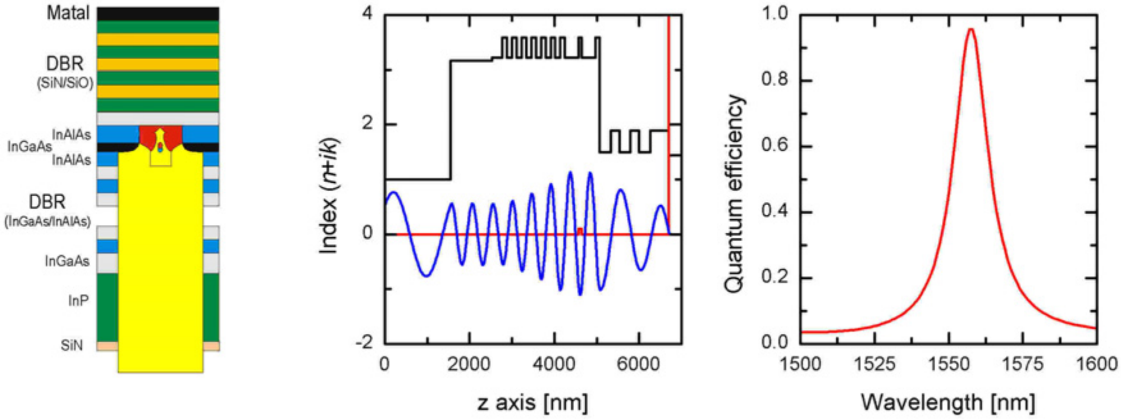

Fig. 3. RCE-PD employing two DBRs consisting from 7 epitaxial pairs of (InGaAs/InAlAs):Si and 3 pairs of SiO_2/Si_3N_4, a scheme of the structure, light is introduced from the substrate side (a), spatial distribution of the refractive index (b), spectral response of the detector (c)

The resonance spectral width is described by the finesse:

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{m_c F}$$

where the m_c is the cavity order. Higher mirror reflectivity higher the finesse and the resonant wavelength is better defined. Often the quality (Q) factor is used rather then the finesse

$$Q = \frac{2n\pi}{\lambda} L \frac{\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

The quality factor is the function of the mirror reflectivity and describes increase of the mode amplitude in the antinodes position of the standing wave.

For high reflectivity of the cavity mirrors high finesse, high quality factor the electromagnetic field strongly increases inside the cavity. By placing an absorption layer in a antinode position of the standing wave the absorption is enhanced. From this benefit a Resonant-Cavity Enhanced Photo-Detector.

The simplest RCE-PD it is a photo-detector employing a single DBR as in case described above but without the antireflection coating [5]. The refraction index step on the semiconductor –air interface cause ~0.3 reflection of the light. This is enough to enhance absorption on very thin layers [6,7,8,9].

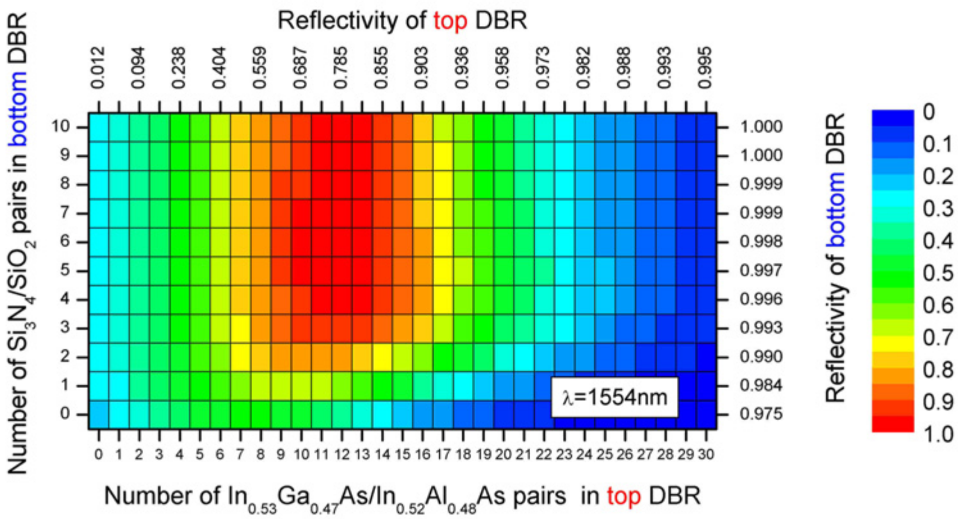

Fig. 4. RCE-PD quantum efficiency as the function of the mirror reflectivity i.e., number of high/low index pairs in the epitaxial DBR and hybrid DBR+metal mirror and the absorption layer 67nm thick.

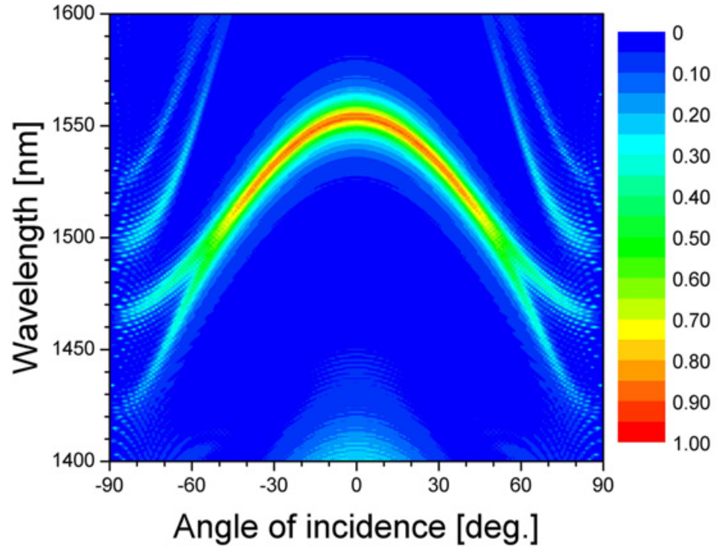

Fig. 5. RCE-PD quantum efficiency as a function of wavelength and angle of incidence. Data calculated for 7 pairs of InGaAs/InAlAs epitaxial DBR and 3 pairs of SiO_2/Si_3N_4 in hybrid DBR.

Since the reflection on semiconductor/air interface has a constant value what limits the flexibility of the design an alternative new design of RCE-PD is presented here (Fig. 3). To the proposed device the light is introduced from the substrate side. The heterostructure consist from a heavily ($n=10^{19}cm^{-3}$) doped (InGaAs/InAlAs):Si DBR epitaxialy grown on InP substrate followed by a InAlAs cavity with a thin (67nm) InGaAs absorption layer located in a antinode position. On top of the heterostructure second DBR is fabricated in separated technological step from SiO_2/Si_3N_4 coated with a metal layer. Such hybrid DBR+metal mirror assures very high reflectivity of back mirror what limits the light leakage.

The optimum reflectivity of the cavity enclosing mirror has bean calculated using as before transfer matrix formalism, the data is presented in Fig. 4. There is clearly visible that the optimum reflectivity of the front mirror is in the middle value range ~0.75, whereas the back mirror should have as high reflectivity as possible. Since than it seems that the optimum number of high/low index pairs in DBR is 7 and 3 in epitaxial and hybrid mirror, respectively. Such small values make the epitaxial and fabrication process easy and straightforward. For those numbers of pairs the absorption has been also calculated as the function of wavelength and absorbing layer thickness (Fig. 5). The data shows very rapid increase of the absorption for very thin absorption layers when the thickness is increased and saturation of the absorption for thicker layers. The absorption equal to 0.9 on the layer only 67nm thick can be compared to the absorption in the conventional PD on 3100nm thick layer i.e., 40 times thicker. Such huge reduction of the absorbing layer thickness results in similar increase in the bandwidth since the carrier transition time is proportional to the layer thickness.

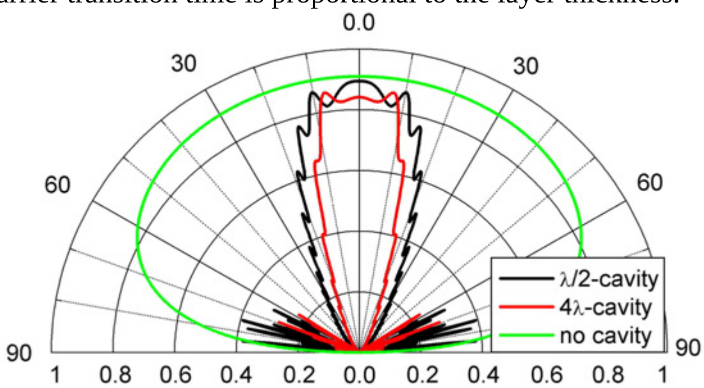

Fig. 6. Comparison of quantum efficiency versus angle of incidence for RCE-PD and conventional photo-detector for which no cavity is applied.

The RCE-PD offer the increase in the bandwidth but in expense of the spectral width. In place of the flat spectral response of the conventional PD the RCE-PD is sensitive only in very narrow band (Fig. 4). The spectral width of the RCE-PD response depends on the cavity *Q*-factor. For high *Q* cavities the wavelength selectivity of the PD increases what can limit it application. For low *Q* factor cavities the RCE-PD spectral response broadens but than the thicker absorption layer has to be used since the cavity enhancement of electromagnetic field amplitude is smaller. High *Q* factor cavities make the PD also very illumination angle sensitive. This is because RCE-PD employ one dimensional cavities. For one dimensional cavities only the *z* (let's assume that *z* axis is perpendicular to the layer surface- parallel to the growth direction) co-ordinate k_z of the wave vector *k* is in resonance with the cavity. If the angle of incidence is increased also the length of the *k*-vector has to be increased in such a way that the *z* co-ordinate stays constant. Grater *k*-vector shorter the resonant wavelength ($\lambda=2\pi/k$) (Fig. 5). For the designed heterostructure the angle dependent wavelength shift is in the 80nm range. At the same time the angle quantum efficiency of the PD for the wavelength for which is dedicated drops by half for the angle deviation smaller 20 deg. The precise value depends on the particular design of the device. For the large cavities i.e., corresponding to the elevated number of half wavelengths this value is even smaller (Fig. 6).

4. Conclusions

Enclosing active region by two dimensional cavity the quantum efficiency of o PD can be efficiently enhanced. The medium *Q*-factor cavity allows to decrease the absorption layer thickness over tenfold. Such huge reduction in the carrier transition times can result in increases of the bandwidth thus gives new opportunities to the semiconductors photo-detectors application when high response speed is required. The unique spectro-angular sensitivity make them an interesting device for wavelength sensitive detection of radiation in, for instance, spectrometric application. However RCE-PD are no simple substitution for the conventional PD. The resonant cavity which allows to solve the high speed high-quantum efficiency contradiction and makes those PD superior in above mentioned application limits also it wide use. The flat spectral response of conventional or single mirror PD is often its asset.

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