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Analysis of the *nBn*-type Barrier Structures for Infrared Photodiode Detectors

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Abstract—Modern trends in the technology of $Cd_xHg_{1-x}Te$-based photosensitive barrier structures for the middle and far infrared bands, which can operate at near-room temperatures, are analyzed. Main approaches to solving the problem of increasing the photodiode-detector operating temperature have been considered and analyzed.

Keywords: MCT, $Cd_xHg_{1-x}Te$, photodetector, barrier structure, *nBn*
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INTRODUCTION

It is known that semiconductor infrared (IR) photodetectors must be deeply cooled to have high sensitivity and reduced noise. The need in cooling is due to a rather high level of heat generation of charge carriers in the narrow-band semiconducting material.

In connection to this, a large number of fundamental and applied studies are now devoted to seeking new ways of improving the characteristics and reducing the cost of IR photodetectors, including development of new types of photodetectors. The major trend in the development of the technology of IR photodetectors is to increase the operating temperature of the device and, in future, abandon cryogenic systems, which significantly raise the cost of the device and limit the area of its application.

The main approach to minimization of thermal generation in the active region of the detector without using cryogenic cooling systems is to suppress the Auger mechanisms with nonequilibrium depletion of the semiconductor [1] and use new natural and modified semiconductor materials and semiconductor structures with reduced thermal generation. In 2006, Maimon and Wicks [2] proposed the concept of the so-called photosensitive *nBn* barrier structure, which is often structurally compared to the classical *p*–*n* photodiode, in which the space-charge region of the *p*–*n* junction is replaced with wide-band barrier *B*, and the *p*-region is replaced with an *n*-type contact. The second layer acts as an active absorbing region. Due to introduction of a wide-band barrier at a negatively biased structure (when a negative potential is applied to the *n*-type contact), a potential barrier is formed for the majority carriers (electrons in the case of the *nBn* structure) and dark currents caused by the majority carriers are suppressed; however, no barrier is formed for the current of the photogenerated minority carriers [3]. Introduction of a wide barrier instead of the space-charge region of the *p*–*n* photodiode reduces also the contribution of the Shockley–Read–Hall generation–recombination mechanism to the dark current.

The main problem in constructing the *nBn* photodiodes based on the CdHgTe (MCT) material is that, in contrast to materials of group A^3B^5 (for which the concept of barrier structures has been initially proposed), the discontinuity of the the valence band in MCT-based heterostructures is considerable. As a result, a certain potential barrier is also formed for the minority carriers, which negatively affects the advantages offered by the use of the *nBn* structures.

ANALYSIS OF THE LITERATURE DATA

It follows from the above that the main problem in constructing MCT-based *nBn* photodetectors with characteristics corresponding to those of MCT-based *p*–*n* photodiodes is to remove the barrier for the minority carriers in the structure. There are several solutions of this problem.

Increase of the external bias. The energy diagram of an *nBn* heterostructure with a $Cd_{0.275}Hg_{0.725}Te$ absorbing layer and a three-layer barrier whose central part consisted of $Cd_{0.55}Hg_{0.45}Te$ whereas the boundary layers were variband structures whose compositions smoothly varied to those of the contact and absorbing

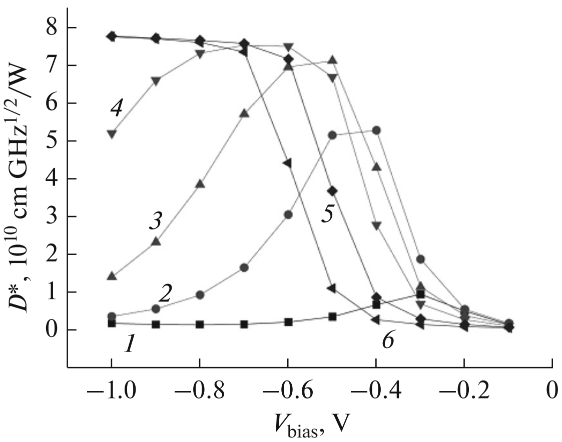

Fig. 1. Calculated detectability of the *nBn* photodetector considered in [4] as a function of the external bias at various compositions of the barrier layer: x_{bar} = (*1*) 0.45, (*2*) 0.5, (*3*) 0.525, (*4*) 0.55, (*5*) 0.6, and (*6*) 0.65.

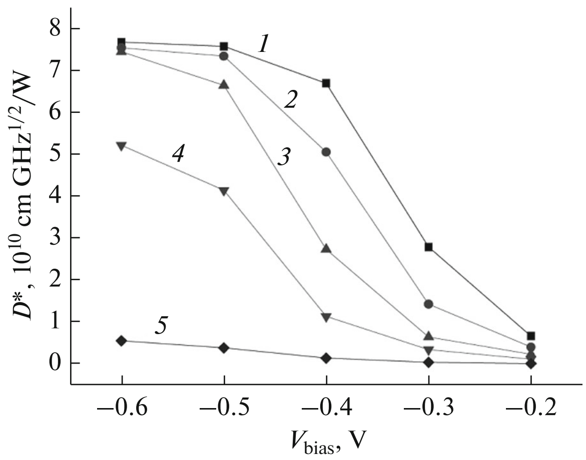

Fig. 2. Calculated detectability of the *nBn* photodetector considered in [4] as a function of the external bias at various compositions of the contact layer: x_{cont} = (*1*) 0.2, (*2*) 0.25, (*3*) 0.3, (*4*) 0.35, and (*5*) 0.4.

layers was simulated in [4]. It should be noted that, in the structure under consideration, a nonuniform profile of the *n*-type dopant was used. In this paper, the detectability of the structure and a photodiode on its basis were simulated. The calculations were performed for a detector temperature of 180 K.

Figures 1 and 2 show the results of simulation of the photodetector detectability at various negative biases and various structure parameters (compositions of the barrier and contact layers).

It can be seen from the plots presented in Fig. 1 that the barrier layers with a higher composition provide better values of device detectability D^*, a fact that can be explained by a more efficient shielding of the current of majority carriers in the structure with a wider energy gap. In this case, the presence of the barrier for holes in the valence band determines low values of the detectability at zero and low (up to −0.3 V) external biases. As the negative external bias increases, the geometry of the potential barriers undergoes considerable changes for both electrons and holes. When the bias increases, the height of the barrier for holes becomes lower, a factor that lowers the barrier for the minority-carrier current and results in an increase in the detectability. However, if the bias values are too high (e.g., more than −0.6 V for a barrier composition with a mole fraction of 0.55), the change in the barrier shape in the conduction band becomes significant: the barrier shape tends to become triangular, the tunnel transparency of the barrier increases, and the efficiency of the shielding of the majority-carrier current decreases. As a result, the detectability of the device decreases.

The effect of the contact layer composition on the detectability of the photosensitive *nBn* structure can be described in a similar way (see Fig. 2). An increase in the composition of the contact layer will lead to a decrease in the conduction gap ΔE_c, which will negatively affect shielding of the majority-carrier current.

Similar results were also obtained in [5, 6].

Control of the parameters of the barrier layer. This mechanism was described, e.g., in [3, 7]. The essence of the technique is to select the barrier parameters (polarity of conduction, doping level, thickness, and composition) in order to minimize the barrier for minority carriers in the structure. According to the theoretical and experimental studies described in the literature, structures with *p*-type barriers exhibit better characteristics than structures with *n*-type barriers. According to [7], at a certain external bias, the potential barrier for holes can be almost completely removed by precision *p*-type doping of the barrier region. The data presented in this paper confirm that, in the case of the *p*-type doping of the barrier layer at an external bias of −0.6 V, the barrier for holes can be almost completely removed.

However, it should be noted that the process of growing of MCT heterostructures by means of molecular beam epitaxy makes it possible to obtain a material with *p*-type conduction only after ex situ activation of implanted acceptors, a circumstance that imposes severe restrictions on practical implementation of mass production of nB_pn photodiodes. Hence, the use of the *p*-type barrier is justified in the case of growing heterosructures by means of the metal–organic chemical-vapor deposition (MOCVD), which makes it possible to obtain in situ materials with conductions of both donor and acceptor types.

Application of multilayer barriers, including barriers in the form of superlattices. The authors of study [8] confirm by their research the conclusions that the *p*-type barrier layer can considerable reduce the potential barrier for holes. However, introduction of a bar-

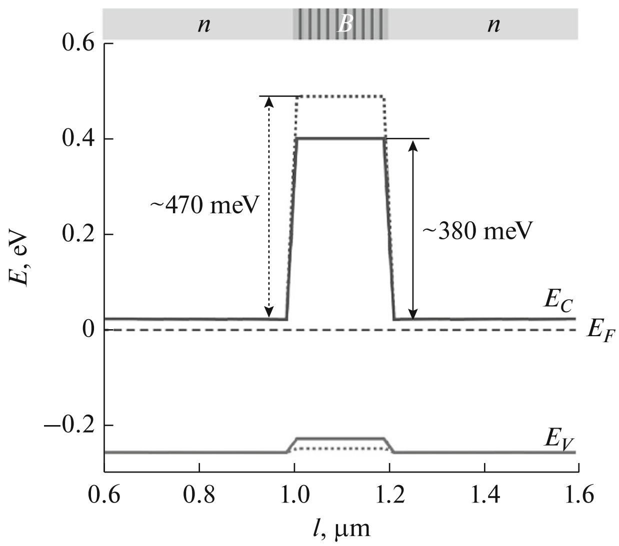

Fig. 3. Calculated energy band diagrams of the structures with barriers in the form of a type-III superlattice (T3SL) at a temperature of 80 K under the zero external bias [8] for two superlattice configurations. Solid and dashed curves correspond to structures 6/28 and 5/28, respectively.

rier layer with *p*-type conduction into a structure with *n*-type conduction leads to formation of space-charge regions near interfaces of the contact *n* layer–*p*-type barrier and *p*-type barrier–absorbing *n* layer, which in turn leads to an increase in the contribution to the dark current of the generation–recombination component (Shockley–Read–Hall mechanism). Hence, the advantage offered by the use of the barrier doped with acceptor dopant is not obvious and needs to be proved in detail.

The authors of study [8] proposed a radically new approach to solving the problem of removal of the barrier for minority carriers. Figure 3 shows energy band diagrams $E(l)$ calculated by the authors for the structures with barriers in the form of superlattices with two different configurations: 6 HgTe monolayers/28 $Cd_{0.95}Hg_{0.05}Te$ monolayers and 5 HgTe monolayers/28 $Cd_{0.95}Hg_{0.05}Te$ monolayers. The simulation carried out by the authors of that study allows us to conclude that a barrier structure of this kind can completely remove the potential barrier for holes without introduction of space-charge regions.

There are also several studies in which, in addition to the above methods for improving the operating efficiency of the photosensitive *nBn*-structure, optimization of the structural components is used. For example, in [3], various structures of the contact layer are analyzed and a pronounced effect of the contact configuration on the current–voltage characteristics and the sensitivity of the device is demonstrated.

CONCLUSIONS

The results presented have shown that *nBn*-type barrier structures can be used as an alternative to far- and middle-infrared photodiode detectors owing to the possibility of optimization of the barrier structure aimed at lowering of dark currents and increase of the sensitivity. The use of these barriers makes it possible to exclude the operation of manufacturing of the *p*-region in the initial *n*-type heterostructure from the process of growing of the photodiode structure, , i.e., doping with the acceptor dopant (including complete implantation), and subsequent activation annealing.

Currently, there are several unsolved design and manufacturing problems in the development of such detectors. The presence of the barrier for holes in the valence band in the MCT-based *nBn* structures requires certain technological solutions, namely: application of high values of the external bias; control of the parameters of the barrier layer, including acceptor doping of the barrier; and the use of complex multilayer barriers.

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