FIR ABSORPTION IN \( p \)-GaAs HIWIP DETECTORS STRUCTURES WITH THICK INTRINSIC LAYERS

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Responsivity of \( p \)-GaAs homojunction interfacial work-function internal photoemission detectors with optical cavity architecture has been measured for wavelengths 20–100 \( \mu \)m. The intrinsic region thickness and the bottom contact layer are used to obtain the cavity effect. Increased responsivity due to increased absorption is verified by using detector structures with different distances from the top emitter to the bottom contact layer.

1. INTRODUCTION

Recently reported homojunction interfacial work-function internal photoemission (HIWIP) far infrared (FIR) detectors [1] compete with extrinsic Ge photodetectors (unstressed or stressed) and Ge blocked-impurity-band (BIB) detectors due to the material advantage of GaAs over Ge. The detection mechanism of HIWIP detectors involves absorption in the highly doped emitter layers mainly by free carriers followed by the internal photoemission of photocreated carriers across the junction barrier and then collection. The cutoff wavelength \( \lambda_c \) is determined by the interfacial barrier height between the emitter layers and undoped intrinsic layers [2].

A typical \( p^+\)–\( i \) HIWIP structure consists of a heavily doped emitter layer, the intrinsic (or lightly doped) layer, the bottom contact layer, having thicknesses \( W_e \), \( W_i \), and \( W_m \), with corresponding doping concentrations \( N_e \), \( N_i \), and \( N_m \) (see inset in Fig. 1). Several units of emitter-intrinsic layers could be present (for one of the structures studied so far). For the structure with \( N \to N_e \) repeated and the thickness of the top emitter layer \( W_e \), the total thickness is \( W_T = W_{m} + W_{i} + N(W_{e} + W_{i}) + W_{m} \). Unavoidable presence of an optically thick bottom contact layer results in high reflection of the radiation that is not absorbed by the emitter/absorber in the first pass through. Emitters placed close to the bottom contact doesn’t absorb effectively due to low value of optical electric field near the node of formed standing wave. To increase the absorption in active layers, the last should be placed at approximately \( \lambda_c/4 \), where \( \lambda_c \) is the wavelength inside the medium. Significant progress has already been achieved in the development of SI emitter \( p \)-GaAs HIWIP FIR detector with \( W_T = 2.16 \mu \)m, resulting in detectivity of \( 5.9 \cdot 10^{10} \) \( \text{cm} \cdot \text{Hz}^{1/2} / \text{W} \), with \( \lambda_c \) as long as 100 \( \mu \)m [1]. In [3] the possibility of creating detectors with optimal geometry for different wavelengths is discussed. This paper presents the experimental verification of the increase of FIR response of the HIWIP detector with increasing \( W_T \) to \( \lambda_c/4 \) value.

2. EXPERIMENT

Three \( p^+\)–\( i \) GaAs samples grown by MBE were under investigation. The layer parameters are presented in the Table. Sample # 9901 contains one emitter layer placed at 4 \( \mu \)m from the bottom contact layer. Sample # 9902 contains one emitter (as in the first sample) separated from the bottom contact with 1 \( \mu \)m thick \( i \)-region. Sample # 9903 contains four emitter regions separated with 1 \( \mu \)m thick \( i \)-region (as in the second sample), so the distance from the top emitter to the bottom contact layer is approximately the same as in the first sample. Emitter concentration \( N_e = 4 \cdot 10^{19} \) \( \text{cm}^{-3} \), contact layer concentration \( N_c = 2 \cdot 10^{19} \) \( \text{cm}^{-3} \) were the same for all three structures. Such a sample set allowed demonstrating a significant increase in absorption with increasing the distance from the top emitter to the bottom contact, as far as the broadening the spectral response in multi-emitter structures discussed in [4].

The experimental responsivity of the detectors at 4.2 K for forward and reverse biases is shown in Fig. 1. Spectral response was measured with a Perkin-Elmer system 2000 FTIR spectrometer with resolution of 4 \( \text{cm}^{-1} \) and then normalized by the response of the calibrated Ge bolometer in the same optical scheme. All three structure demonstrated response with cutoff wavelength \( \lambda_c = 80 \mu \)m, which is consistent with the interfacial barrier height between the emitter layer and undoped intrinsic layer, determined by \( N_e \) [2]. For all three samples the spectral response consists of two bands separated by the deep valley at 37 \( \mu \)m corresponding optical phonon energy in GaAs. Four-emitter structure # 9903 with \( W_T = 4.8 \mu \)m demonstrated maximal responsivity 1.2 \( \cdot 10^{4} \) V/W in the shorter-wavelength band, sample # 9901 with one emitter and \( W_T = 4.7 \mu \)m had 2.7 \( \cdot 10^{4} \) V/W, one-emitter sample with
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Fig. 1. Experimental spectral responsivity at positive bias. Response is maximal for four-emitter sample # 9903 with $W_T = 4.8 \, \mu m$. The inset shows the schematics of tested multi-emitter HIWIP detector. $p^+$ is the contact layer, $p^+$ is the emitter layer, and $i$ is the undoped layer. A window is opened on the top for frontside illumination. Samples # 9901 and 9902 contain only the top emitter. Mesa size was $400 \times 400 \, \mu m^2$ for all tested samples.

$W_T = 1.7 \, \mu m$ had $1.0 \cdot 10^4 \, V/W$ for the same average applied bias field of 200 V/cm.

3. THEORY

Absorption in multilayer GaAs HIWIP detector structures is determined by free-carrier absorption in highly doped regions [4]. Dielectric permittivity $\varepsilon$ of each layer was calculated as combination of "free-carrier" term in the frame of Drude model and the "reststrahlen" term taking into account the interaction with optical phonons in the Lorentz model [5]:

$$\varepsilon = \varepsilon_a \left( 1 - \frac{\omega_p^2}{\omega_c^2} \right) + \frac{\omega_p^2 (\varepsilon_a - \varepsilon_r)}{\omega_c^2 - \omega^2 - i \gamma \omega},$$

Here $\omega$ is the optical frequency, $\omega_c = 1/\tau$ is the free-carrier damping constant with relaxation time $\tau$ (which is considered frequency independent in semi-classical transport theory), $\omega_p = (N_e q^2/\varepsilon_0 \varepsilon_m)^{1/2}$ is the plasma frequency, and $\varepsilon_r$ is the low frequency dielectric constant of an intrinsic semiconductor, $m^* = 0.5 m_0$ is the heavy-hole effective mass in GaAs (one-band model), $m_0$ is the free electron mass, and $q$ is the magnitude of the electron charge. The carrier concentration $N_e$ can be estimated from the doping level: corresponding values

<table>
<thead>
<tr>
<th>Sample #</th>
<th>No. of emitters $N + 1$</th>
<th>$W_{bc}, , \AA$</th>
<th>$W_e, , \AA$</th>
<th>$N_e, , \text{cm}^{-3}$</th>
<th>$W_i, , \AA$</th>
<th>$W_{bc}, , \mu m$</th>
<th>$N_i, , \text{cm}^{-3}$</th>
<th>$W_T, , \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9901</td>
<td>1</td>
<td>150</td>
<td>...</td>
<td>$4 \cdot 10^{18}$</td>
<td>4.0</td>
<td>0.7</td>
<td>$2 \cdot 10^{19}$</td>
<td>4.7</td>
</tr>
<tr>
<td>9902</td>
<td>1</td>
<td>150</td>
<td>...</td>
<td>$4 \cdot 10^{18}$</td>
<td>1.0</td>
<td>0.7</td>
<td>$2 \cdot 10^{19}$</td>
<td>1.7</td>
</tr>
<tr>
<td>9903</td>
<td>4</td>
<td>150</td>
<td>150</td>
<td>$4 \cdot 10^{18}$</td>
<td>1.0</td>
<td>0.7</td>
<td>$2 \cdot 10^{19}$</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Parameters for three p-GaAs HIWIP FIR detector structures with thick $i$-regions, $W_{bc}, W_e, W_i$ - thicknesses of bottom contact, undoped $i$-region, and emitter layer, respectively. $W_T$ is total growth thickness, $N_i$ and $N_e$ - doping concentration (Be) in emitter and contact layers, respectively.
4. RESULTS AND DISCUSSION

Calculated absorption in active layers (emitters) of studied structures is shown in Fig. 2(a). Interference oscillations arising due to reflection from backside of the 350 µm-thick substrate were averaged within a spectral interval of 4 cm⁻¹ modeling the experimental resolution. Figure 2(b) shows absorption in internal emitter layers of sample # 9903.

For all three samples there is a deep valley at 37 µm in absorption spectra. This absorption minimum is connected with the strong reflection from the GaAs at the optical phonon energy. Calculated spectra are in reasonable agreement with experimental responsivity curves. It is seen that response of HIWIP detectors is determined by the free-carrier absorption in emitters. Strong decrease of the detector response at long wavelength is determined by the behavior of quantum efficiency η(λ) of photoemission detector. Quantum efficiency is determined by the height and the shape of the potential barrier between the emitter and i-region, η should be the same for the same emitter doping concentration and the same applied bias field. Responsivity of the detector at fixed wavelength is proportional to the absorption in the emitter layer. Absorption and responsivity are both higher for the samples # 9901 and 9903 with larger \( W_f \). The highest absorption and responsivity realized for multi-emitter sample # 9903 due to additional contribution of internal emitters to the total "active" absorption. For multi-emitter detector # 9903 maximum of responsivity is shifted to the shorter wavelength in comparison with # 9901 with the same \( W_f \) (see Fig. 1). This shift is due to contribution of internal emitters. Longest-wavelength maximum of absorption in n-th emitter tends to satisfy the condition, \( D_s \sim \lambda/4 \), where \( D_s \) is the distance to bottom contact layer. Emitter closer to the bottom contact layer has absorption maximum at shorter wavelength (see Fig. 2(a)).

5. CONCLUSIONS

Significant increase of HIWIP detector responsivity in FIR range was verified experimentally for structures with thick i-regions. The high FIR reflection from the thick layer of highly doped GaAs allows using a bottom contact in HIWIP detector structure as a mirror. The use of optical cavity architecture with corresponding increase doping concentration in emitters (and thus, the cutoff wavelength) gives rise the possibility to extend the range of HIWIP detectors up to 200 µm and beyond, where free carrier absorption remains significant.

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