HgCdTe nanostructures on GaAs and Si substrate for IR and THz radiation detecting

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Abstract. All-round studies of heteroepitaxial HgCdTe nanostructures (NS) growth on GaAs and Si substrates by molecular beam epitaxy have been carried out. In case of Si substrate HgCdTe NS’s is very perspectives for IR detectors because of equal thermal expention coefficient with silicon read-out circuits. The problems of HgCdTe conjugations with Si at epitaxy connected with large differences in lattice mismatch and differences in chemical bonding that leads to antiphased domains. We found that the precise formation of transition layer (2 nm in thickness between Si substrates and first ZnTe buffer layer leads to growth HgCdTe NS’s without antiphasis domains. V-defects and etch pits densities are equal to $10^3$ cm$^{-2}$ and $10^7$ cm$^{-2}$ respectively. The HgCdTe/Si were used for fabric a tion photovoltaic 640×512 MWIR focal plane arrays. The operability for $\lambda_{1/2} = 4.2 \mu$m (77K) was over 97%. The response (Sv) and NETD were as $1.5 \times 10^9$ V/W and less 20 mK respectively. We developed the precise growth of symmetric and antisymmetric HgTe QW. We found the following effects: the presence 2D electron gas with high mobilities over $5 \times 10^5$ cm/V×s in doped HgTe QW, the presence @D holes and electrons in undoped HgTe QW and high sensitivity to linear and circular polarized IR and THz radiation in 6 – 400 μm region.

1. Introduction
A trend of modern infrared (IR) thermal-imaging systems is developing large format focal plane array (FPA). Mercury cadmium telluride (MCT) alloys have an advantage over other photosensitive materials because of unique physical properties [1]. To realize large format IR FPA based on MCT it is necessary to grow material with high lateral composition uniformity that leads to wavelength uniformity. Nanostructures, such as HgTe/CdTe quantum walls (QW) or superlattices (SL) are an alternative material for IR detection with better wavelength cutoff uniformity than in alloys [2]. Recently, considerable effort has been directed to the development of the growth of heteroepitaxial MCT structures by molecular beam epitaxy (MBE) on Si large in diameter substrates [3]. MCT/Si solved the problem of thermal cycling in temperature range 80-300 K of cooled large format IR FPAs as a hybrid assemblage because of equal thermal expansion coefficients of the photosensitive element and a Si read-out circuit (ROIC). The substrate orientation is essentially influence on quality MCT MBE. It was found [4] that MCT MBE growth on the (112)B substrate surface is carried out at low Hg vapor pressures without twin formation that leads to high material quality. However, the (112) orientation is very sensitive to insignificant variations in the growth conditions. That determines a narrow range of optimal growth condition for fabrication MCT MBE with a minimal defect [5]. But intensive development of

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equipment is being carried out for MCT MBE growth on large in diameter (up to 6") (112) Si substrates. It was shown that MCT/Si can be used for fabrication of high quality photonic IR FPAs in a spectral range up to 10 μm [6]. The MCT MBE growth on (013) GaAs substrates [7] have been studied. It was shown that the empirically determined substrate orientation (310) provides growth of high quality MCT/GaAs without stacking faults and twin lamellae also at low Hg pressures in essentially broad interval of optimal growth conditions. The successes in MCT MBE alloys growth on GaAs allows to develop and grow high quality HgTe QW. Recently a detector system for room temperature electric detection of the polarization state of laser beams at terahertz frequencies was realized using low symmetry GaAs and SiGe QWs [8]. In this study, we examined the growth of MCT heterostructures on Si (310) substrates with a diameter as large as 100 mm for IR FPAs of the spectral range of 3–5 μm and the formation and characteristics of p–n junctions and photoelectric parameters of IR photodetectors with different formats. We present the results of reproducible growth of single and multiple (up to 30) HgTe QWs and photogalvanic effect in IR and THz spectral range.

2. MCT MBE growth on Si(310)

2.1 Experimental procedure

MCT MBE on (013)Si had were grown at multichamber ultrahigh vacuum MBE set “Ob” [9]. For monitoring in situ growth processes reflection high-energy electron diffraction (RHEED) and single-wave ellipsometry at wavelength $\lambda = 632.8$ nm was used. (013)Si substrates 76 and 100 mm in diameter were treated by the standard RCA procedure [10] and then hydrogenated into a 1% aqueous HF solution [11]. After loading there is preepitaxial vacuum annealing at 550–600°C in the arsenic flow and cooling. The ZnTe layer 0.01 μm in thickness on Si surface was grown on Si at 200–240°C. The CdTe layer 6–8 μm in thickness was grown on ZnTe/Si at 280–320°C. MCT layers were grown on CdTe/ZnTe/Si(310) substrate by the process which was described in detail in [9]. Special the coaxial arrangement of the molecular sources is realized for growth MCT on GaAs or Si without substrate rotation with very uniform composition distribution over the surface area [12,13]. The calculation shows that the composition uniformity should not exceed 0.0002 cm$^{-1}$. Experimentally the composition gradient $x/l$ over the surface for MCT layers ($x = 0.3–0.35$) less than 0.002 cm$^{-1}$ that leads to wavelength cut-off accuracy at 77 K less than 0.1 μm. Fig. 1 shows MCT MBE growth on Si (a), composition (b) and wavelength cut-off (c) uniformity over the surface area.

![Figure 1](image-url)

Figure 1. The MCT MBE on (013)Si (a) and composition (b, mole fr.) and wavelength cut-off (c, μm) uniformity over the surface area.

We developed passivation procedure of absorber layer by graded wide gap layers [14] at boundaries during the MCT MBE growth. Fig. 2 shows the composition distribution throughout the thickness measured by ellipsometry in situ.
Such graded wide gap layers help to increase minority lifetime [15, 16] and to decrease or eliminate surface leakage [17] in PV FPA. There are the following defects in MCT MBE grown on Si: antiphase domains (APD), stacking faults (SF), threading dislocations (TD) and macroscopic morphological V-defects. Bulk defects were studied by transmission electron microscopy (TEM) and revealed by selective etching. TEM analysis form of thin foils parallel to the growth surface and transverse section was performed using the electron microscope JEM-4000EX (JEOL). We used etchants 10ml HNO3 + 20 ml H2O + 4g K2Cr2O7 + 1,5 mg AgNO3 (E-Ag1) [9] and 5g CrO3 + 3 ml HCl + 15 ml H2O (etchant Schaake) [10] for selective etching of CdTe and MCT layers respectively. The etching pits (ND) were as elongated triangles for CdTe and points for MCT. APD boundaries were identified as lines of arbitrary shape. SF was represented in the form of parallel straight lines. The surface defect (V-defect, etching pits and lines) densities and sizes were measured using optical microscope equipped by scanning system and built-in CCD camera.

2.2 Antiphase domains

The detailed mechanism of the APD formation is developed in [11]. The APD formation at III-V or II-VI layers grown on Si substrates is due to the monatomic of silicon surface. Fig. 3a shows the scheme of the deposition on monatomic Si at first As and then Ga atoms which leads to APD. So to cancel the formation APD it is necessary diatomic Si surface. Fig. 3b represents the growth GaAs on Si without formation APD. But for growth ZnTe on Si the presence of diatomic steps on the silicon surface is not enough to grow films without APD. Really clean Si surface after preepitaxial annealing is interacted with species in residual vacuum created contamination centers which leads to defects formation. For elimination contamination at clean Si surface the passivation is carried out by As at preepitaxial annealing. It was experimentally shown that the absence of As on (211) Si leads to polycrystalline CdTe growth. It is known that Zn or Te is absorbed in the form of separate islands of As/Si(310) or clean Si(310) surfaces [18]. That can be the other reasons for APD formation at ZnTe growth.

We investigated the dependence of preepitaxial condition (different temperatures 500-1250 °C) on Si surface morphology by LEED and STM. We found the optimal condition of formation diatomic step Si surface, Nevertheless APD could occur in HgCdTe/CdTe/ZnTe/Si(310). Fig. 4 shows (100) TEM images of foil prepared from CdTe/ZnTe/Si(310) with APD formation. It can also be seen that APD gives under view structural damage. This allows us to identify APD by chemical etching in a selective E-Ag1 etchant. We
investigated the growth CdTe (6 - 8 μm)/ZnTe (0.01 - 0.02 μm)/Si(310) for determination of APD appearance and growth conditions of ZnTe. The CdTe growth conditions and preepitaxial preparation processes were the same. It was found that the growth conditions of ZnTe at 200 – 220 °C and Zn/Te2 ~ 5 – 20 leads to growth CdTe/ZnTe/Si without APD (see Fig. 5).

Figure 4. (100) TEM-images of APD in CdTe/ZnTe/Si(310).

Figure 5. Etch pits on the surface of CdTe/ZnTe/Si(310) grown at 200 °C without APD

There are two APD types for ZnTe/Si. These are Si-As-Zn-Te and Si-As-Te-Zn configuration. To determine the probability of APD configuration it is necessary molecular flux of a one component higher in 1 – 2 orders over molecular flux of an other component. A series ZnTe/Si was grown under conditions where Te2/Cd >> 1 to realized Si-As-Te-Zn configuration. However at these conditions ZnTe layers are grown as polycrystalline. So we think that Si-As-14 Zn-Te configuration is more preferably. The growth at Cd/Te2 >> 1 leads to crystalline ZnTe and in optimal condition without APD.

2.3 Stacking faults
SF in HgCdTe/CdTe/ZnTe/Si(310) are a subtracting type with the density of 10^{5}-10^{7} cm^{-2}, lie parallel planes (111) intersecting the plane (310) at an angle of 68.58 degrees and nucleate at ZnTe/Si(310) interface and grow throughout the film up to surface (see Fig. 6). Selective etching revealed SF in the form of parallel straight lines. There are several reasons of the formation of stacking faults in heteroepitaxy of semiconductors with a sphalerite lattice. It must be taken into account that SF occurs only in one of four possible {111} planes in CdHgTe/CdTe/ZnTe/Si(310). The proposed model must explain not only the formation of SF but also their anisotropy. Two {111} planes form an angle of 43.09° with the (310)-plane and the other two - 68.58°. SF lying to the boundary at a smaller angle will have a larger area than SF lying at a larger angle with the same thickness of the grown layer. Accordingly, they will have a large excess energy and their formation will not be profitable. The two remaining SF lie in (111) planes with different polarity. It remains to understand why one of the two different polar planes is preferable to another. The detailed investigation of formation of SF was studied in ZnSe/GaAs(100). The maximum SF observed at 3-D growth [19] and formed on the (111) facets that occur on the slopes of three-dimensional islands [20].
The lattice mismatch between film and substrate for ZnTe/Si (310) heterostructure is $f = 12.3\%$. Therefore, the formation of SF can be caused by misfit strain in a heterojunction (formation of partial dislocations at the initial stage of stress relaxation). An indirect confirmation of this fact is, firstly, the type of SF (nearly all stacking faults have subtraction type and formed by sliding of Shockley partial dislocations) and, secondly, the formation of SF occurs in closely spaced parallel planes (111). In addition to the deformation mechanism there is also the growth mechanism of the formation of SF in ZnTe/Si. Such a mechanism is realized when a coalescence of three-dimensional islands occurs at the initial stage of growth. The confirmation of growth mechanism of SF formation in HgCdTe/CdTe/ZnTe/Si(310) is observed correlation between the SF density and ZnTe growth rate. We found the decreasing SF density in ZnTe/Si at de crescendo growth rate. It was shown that thermal annealing of HgCdTe/CdTe/ZnTe/Si(310) in inert atmosphere at a temperature of 200 - 250°C for 5 - 10 hours leads to the disappearance of stacking faults in the whole volume of HgCdTe layer. Thermal annealing of CdTe/ZnTe/Si(310) in tellurium at 350°C leads to SF disappearance.

2.4 Threading dislocations

The TD density (NTD) in the epitaxial film decreased from the interface to the surface and described by the equation:

$$\frac{dN_{DS}(x)}{dx} = -aN_{DS}(x) - bN_{DS}^2(x)$$

where $x$ – coordinate (interface at $x = 0$ and surface at $x = h$), $a$ and $b$-constants [21].

The interaction of dislocations (second term in (1) is the dominant process at small thicknesses ($h < 50 \text{ mm}$) typical for the MBE and the solution of equation expressed as:

Molecular-beam epitaxy, as a rule, provides the $N_{TD} \sim 10^5-10^6 \text{ cm}^{-2}$ values in surface regions of films at thickness more 5 microns. This expression is satisfactorily described experimental data with $b = (7.0-9.0) \times 10^{-5}$.

That is the final density of threading dislocations in CdTe / Si (310) heterostructures is determined by reactions between pairs of dislocations with identical Burgers vectors. It was found that the dislocation density in the surface region $N_{TD} \sim 10^7 \text{ cm}^{-2}$ at the surface of CdTe layer $h=5 \mu\text{m}$ grown on Si (310). Further reduction of $N_{TD}$ without increasing the thickness of the film requires new decisions.

2.4 Morphological V-defects

V-defects (void) is specific defects may be called as a “visit card” of MBE MCT. The nature of this defect was connected with possibility of tellurium crystallization at initial stage of MCT growth and during the growth. The
thermodynamic analysis shows that at MCT MBE growth condition (low growth temperature ~ 180-190 °C) there are two solid phases such as MCT and Te may be exist [19]. So at increasing temperatures and decreasing Hg pressure the formation of a polycrystalline film of tellurium is observed experimentally at these temperatures by RHEED in situ. The V-defect formation is due the Te nature at growth. The tellurium evaporates and reaches the MCT growing surface as a diatomic molecule Te$_2$. At low growth temperatures Te$_2$ which do not react with mercury and cadmium can not be evaporated and crystallized as solid phase. The formation of tellurium phase on the surface leads to avalanche multiplication of polycrystalline MCT growth and to V-defect formation. Fig. 7 shows AFM and TEM images of V-defects. It is well known that defects are as “killer” of diodes parameters fabricating on MCT MBE. The presence of V-defect in n-p junction gives linear volt-ampere characteristic that do not allow resisted radiation. Nevertheless, for practical device applications especially for miltielement pixels FPA MCT MBE with V-defects density lower 10$^3$ cm$^2$ is widely used. The process of growing MCT film with a low density of V-defects requires precise maintenance of the growth conditions and high surface quality of the buffer layer. When growth conditions deffer from optimal ones there is not possibility to grow MCT MBE od high crystal perfection with device production request. The results of selective etching allow to find correlation between V-defects density and AD density. To optimize the conditions of preepitaxial preparation processes of the substrate and growth of ZnTe and CdTe buffer layers it is obtained MCT on Si(310) without AD that reduced the V-defects density to values lower 2000 cm$^{-2}$ (see Fig. 8).

Figure 7. Typical AFM (a) и TEM (b) 12×12 μm$^2$ images of a V-defect consisting of stacking faults, twin lamellaes и structure defects on the surface of MCT MBE on Si or GaAs (310).
2.5 Electrophysical characteristics

As-grown undoped MCT MBE on GaAs or Si substrates are n-type conductivity. P-type conductivity were obtained by thermal annealing in a helium atmosphere during 20 hours. The thermal annealing at Hg atmosphere gives again n-type conductivity. The carriers concentration in n-type films are \((1-10) \times 10^{14} \text{ cm}^{-3}\). We suggested that the residual donor at MCT MBE growth is anti-site tellurium atoms [22]. P-type MCT MVE after thermal annealing is determined by Hg vacancies. The majority mobility and minority lifetime of charge carriers in MCT/Si is lower than in the MCT/CdZnTe. Especially noticeable difference is observed for the n-type conductivity. We found that for MCT \((x = 0.3)\) electrons mobility in n-type are weakly decreased with increasing of TD density. In case of SF electron mobility is close to the theoretical values \(40000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}\) at SF densities lower \(2.5 \times 10^6 \text{ cm}^{-2}\). At SF densities \((2.5-5.5) \times 10^6 \text{ cm}^{-2}\) electron mobility varies from to high values. At SF densities more than \(5.5 \times 10^6 \text{ cm}^{-2}\) electron mobility is low values. It is clear that it is possible to grow MCT MBE on Si with high carrier mobility close to the theoretical ones despite the presence of stacking faults.

2.6 Focal plane arrays

2.6.1 MWIR

MWIR photodiodes arrays 320×256 (pixel size 30 μm) and 640×512 (pixel size 25 μm) “N+-p” type were fabricated from the p-type MCT \(x=0.29–0.33\) by B+ implantation. The current–voltage (I–V) characteristics, differential resistance, and ampere–watt sensitivity of photodiodes were measured at 77K. Fig. 9 shows the dependence of dark current \((I_d)\) under a bias voltage of \(-100\) mV on the inverse temperature. It is seen that, in temperature 160–300 K, the dark current is proportional to \(n_i^2\) and determined by the diffusion mechanism [23]. In temperature 140–160K \(I_d\) is proportional to \(n_i\) and determined by generation–recombination processes in the depletion region. The photocurrent \(I_{ph}\) has a maximum value at 160–180 K. At temperatures 77-160 K \(I_{ph}\) increases with temperature increasing. It is explained by continuously increasing carriers diffusion length in temperatures 50-210 K due to an increase in the lifetime [24]. So we conclude that photodiodes characteristics are determined by background radiation up to 170K. The \(R_0A\) product is near \(10^6 \Omega\text{cm}\). FPA was fabricated on photodiode arrays and silicon ROIC by In bumps hybrid assembly. The measurements showed that FPA operability is more than more 98% (the beat more 99%). The defect pixels are uniformly distributed over the FPA area and do not form clusters in the central FPA (see Fig. 10 a). Fig. 10 b shows histogram of NETD. Fig. 11 shows the thermal image obtained FPA 640×512 visualized in real time.
Figure 9. The dependence of dark current on temperature for MWIR photodiode. Bias voltage -100 mV, $x=0.328$: dots – experiment; lines – calculation.

Figure 10. The Tomogram of defect pixels (a) and histogram of NETD at 77K (b) of FPA 320× 256 ($\lambda_{1/2} = 5.2 \mu m$).

Figure 11. Thermal image obtained from FPA 640×512 array based on MCT/Si(310)
2.6.2 LWIR
The LWIR photodiodes arrays 288×4 (pixel size 28×25 μm) were fabricated from the p-type MCT. The dark I-V characteristics are determined by different current mechanisms throughout n-p junction: diffusion current; generation-recombination current; band-to-band and trap-assisted tunneling current and surface leakage current. Experimental and calculated current-voltage characteristics for diodes fabricated from MCT (x = 0.231, (\lambda_{1/2}= 9.06 μm are presented in Fig. 12 (a).

![Image]

Figure 12. I-V and differential resistance-voltage characteristics for a typical diode with (\lambda_{1/2}= 9.06 μm): Dots - experiment; lines – calculations.

The main contribution to the total amount of dark current in reverse bias less than 0.6 V is determined by generation in the depletion region and tunneling through traps. The contribution of other mechanisms is negligible. The dependence of the dark current on the reverse bias shown the predominance of the generation-recombination current. The R0A value was calculated from the I–V curves, while the A value was evaluated from the measured photocurrent as described in [Gopal et al., 2001]. Fig. 13 shows R0A product versus cut-off wavelength λ_{1/2} in the photodiodes based on MCT/Si(310) at 77 K.

![Image]

Figure 13. The dependence of R0A product on cutoff wavelength λ_{1/2} for photodiodes at 77 K based on MCT/Si(310).
As can be seen, the R0A product of these photodiodes in 8-12 \( \mu \text{m} \) is below the upper values calculated assuming the limitation by thermal generation (curve 1), while significantly exceeding the values determined for a regime limited by the background noise (curve 2) [25]. Thus, the obtained data are indicative of a high quality of the material, which is a necessary prerequisite for the development of multielement FPAs. The FPAs 288×4 parameters were measured at 77 K. Figure 14 shows tomatogram of the specific detectivity (a) and voltage sensitivity (b).

![Figure 14. Topogram of the specific detectivity (a) and voltage sensitivity (b) of FPA 288×4 at 77K, \( \lambda_{\text{A2}} = 9.5 \mu \text{m} \).](image)

As can be seen, all 288 channels are photosensitive and their characteristics are not inferior to those of the analogous FPA’s based on MCT grown on lattice-matched CdZnTe substrates. The mean specific detectivity (D*) is \( 1.83 \times 10^{11} \text{ cmHz}^{1/2} \text{ W}^{-1} \) at standard deviation of 28\%, while the voltage sensitivity is \( 1.64 \times 10^8 \text{ V/W} \) at standard deviation of 12.4\%. When the linear IRFPAs are employed in technical imaging systems, additional requirements are imposed on the homogeneity of parameters of the elements. In long wavelength FPAs, channels with a specific detectivity below \( 5 \times 10^{10} \text{ cmHz}^{1/2} \text{ W}^{-1} \) are conventionally classified as defect elements. According to this criterion, the presented 288 \( \times 4 \) FPA based on HgCdTe/Si(310) heterostructure has no defect channels, since the minimum specific detectivity is about \( 6 \times 10^{10} \text{ cmHz}^{1/2} \text{ W}^{-1} \). So we showed that undoped hole-type HgCdTe layers with \( x = 0.23 \) grown by MBE on Si(310) substrates ensure high photoelectric parameters limited by background radiation for LWIR FPAs 288×4.

3. HgTe QW MBE on GaAs(310)

3.1 Experimental procedure

Single and multiple HgTe-based QWs structures are shown schematically in Fig. 15 a. The buffer layers of ZnTe (0.3 \( \mu \text{m} \)) and sequence CdTe (5-7 \( \mu \text{m} \)) were grown on an atomic clean surface of (013)GaAs substrate prepared by chemical etching and thermal annealing in As flux in an ultra vacuum chamber. Then 16-22 nm HgTe QWs with 24 nm Hg\text{1-x}Cd\text{x}Te (x \approx 0.7) spacers were grown on the CdTe/ZnTe/GaAs at temperature 180-190 °C. The central part (10 nm) of spacer was doped in situ up to carrier concentration of approximately \( 10^{15} \text{ cm}^{-3} \) using a conventional indium source. An ultrafast single wavelength (\( \lambda = 0.6328 \)) automatic ellipsometer LEF-755 (UFE) was used for layer buffer thickness and MCT composition and thickness control [26]. The evolution of ellipsometric parameters \( \psi \) and \( \Delta \) during the growth of a single HgTe-based QW is shown in Fig. 15 b. It is represented as a sectionally smooth curve in the \( \psi-\Delta \) plane. Smooth sections correspond to constant MCT composition layers growth. Their length determines layer thickness. The initial point O corresponds to the ellipsometric parameters of CdTe surface.
The fabrication of QW is beginning from the first spacer layer (x ~ 0.7) growth (curve O-A). The doping of central part of this layer is carried out by indium after opening in O’ and closing in A’ of the indium source shutter. Then the growth of wide-gap layer is continued up to point A. In the insertions, the sectors O-O’, O’-A’ and A’-A correspond to those undoped with thickness $d_1$, to In-doped with the thickness $d_2$ and to the undoped wide-gap layer with the thickness $d_3$ parts of spacer layer, respectively. After the closing of the cadmium source shutter, HgTe layer in thickness $d_{QW}$ is growing and ellipsometric parameters $\psi$ and $\Delta$ are changing between A-B points of dependence in $\psi$-$\Delta$ plane. The second spacer layer (see B-C curve) is growing in a manner which is analogous to the growth of the first spacer layer (O-A curve). The thicknesses $d_4$, $d_6$ and $d_5$ correspond to undoped, In-doped and undoped parts of the second spacer layer. The grown single QW structure is covered by CdTe cap layer in thickness $d_{CdTe} \approx 40$ nm. The dots on the curve are experimental data which are measured with a 1 s interval. The circles correspond to calculated values of the ellipsometric parameters through 1 nm in the thickness interval. The calculations were carried out using a one-layer model [27].

Multiple HgTe QWs were grown as periodic HgTe QW structures. Fig. 16 a shows the experimental ellipsometric trajectory measured during the growth of multiple HgTe QW. The curve breaks at each interface and, after approximately ten alterations, displays a nearly reproducible variation between points $P_1$ and $P_2$. This proves periodicity of growing structure parameters, layers composition and thickness. Fig. 16 b shows the thicknesses for all layers of the 30 multiple HgTe QW obtained by calculation from the experimental trajectory in Fig. 16 a. The average period of the structure is 37.7 nm ($d_1 = 21.1$ and $d_2 = 16.6$ nm). There is some dispersion in thicknesses, though the structure is periodical. It should be possible to improve the fabrication quality of the periodic structure by building feedback control implying automatic regulation (adjustment) of molecular sources relying on ellipsometric measurements.
3.2 Electrophysical parameter.

Magnetotransport measurements of Hall bar HgTe QW were carried out in magnetic fields up to 17 T and temperatures from 50 mK to 3 K. Typical HgTe QW width 16 nm and 21 nm were investigated. Fig. 17 shows the \( \rho_{xx}(B) \) and the Hall resistivity \( \rho_{xy}(B) \) in the temperature range (0.3-3) K and in magnetic fields up to 13 T. One can see an ordinary QHE behavior beginning at \( B = 2 \) T with a wide plateau in the \( \rho_{xy} \) and a corresponding wide minimum in the \( \rho_{xx} \). A behavior resembling a magnetic field induced QH liquid-insulator transition is observed at \( T < 1.6 \) K after the Fermi energy crosses the lowest Landau level. The transition is characterized by a critical magnetic field \( B_c = 10.9 \) T and a critical diagonal resistivity value \( \rho_{xx} = 0.9 h/e^2 \). The quantum Hall effect investigations confirmed the high quality of HgTe QW. The observed magnetoresistances behavior is consistent with two-dimensional electron gas. Electron mobility at \( T = 1.6 \) K was \((2.4-3.5) \times 10^5 \) cm\(^2\)/Vs for electron concentration \( N_s = (1.5-3) \times 10^{11} \) cm\(^{-2}\) revealing the high quality of grown QW.

Figure 16. The ellipsometric parameters evolution at 30 multiple HgTe QW growth (a) and thickness calculation from experimental data (b).

Figure 17. The longitudinal and the Hall resistance versus magnetic field in a 21 nm wide HgTe QW. The traces are taken at temperatures \( T = 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 1; 1.2; 1.6; 2 \) and \( 3 \) K.
3.3 Detector application

We found a large sensitivity of HgTe QW to polarised radiation. The photocurrents were induced by direct band-to-band optical transitions or indirect intrasubband (Drude-like) optical transitions in the lowest size-quantized subband applying mid-infrared (MIR) or terahertz (THz) radiation, respectively. Figure 17a shows the helicity dependence of the photocurrent measured at room temperature. The photocurrent was excited by THz radiation with wavelength $\lambda = 148 \mu m$ and power $P \approx 5$ kW from two perpendicular pairs of contacts. The solid lines are fits to phenomenological equations. Insets show corresponding experimental geometries. Along the top the polarization ellipses corresponding to key phase angles $\theta'$ are sketched. The effect is observed in a wide spectral and temperature range, from 6 $\mu m$ to 496 $\mu m$ and from 4.2 K to 300 K.

Figure 17. Photocurrent as a function of radiation helicity measured at room temperature in HgTe QWs grown on (013)-oriented GaAs substrates (a) and thickness calculation from experimental data (b).

Depending on the radiation wavelength and/or sample temperature the currents in both $x'$ and $y'$ directions can be well fitted simply by $J = J_0 \times \sin^2\theta \times P_{\text{circ}}$ (as for the circumstances of Fig. 1) or by more complex dependence on the angle (see Fig. 3) given by $J = A \times \sin^2\theta + B \times \sin^4\theta + C \times \cos^4\theta + D$. (1) Here, A, B, C, and D are fitting parameters. The wavelength dependence of $J_{x'}$ and $J_{y'}$ components are shown in Fig. 17b. We attribute the observed time constant to the bandwidth of our electronic setup. A fast response is typical for photogalvanics where the signal decay time is determined by the momentum relaxation time being in our samples of the order of 0.3 ps at room temperature. As a large dynamic range is important for detection of laser radiation, we investigated the dependence of the sensitivity of the detection system on the radiation intensity applying cw and high-power pulsed radiation. We observed that the ellipticity detector at homogeneous irradiation of the whole sample remains linear up to 2 MW/cm$^2$ over more than nine orders of magnitude.

4. Conclusion

Investigations of growth processes of MCT MBE on Si(310) substrates for 3rd generation FPAs were carried out. It was shown that the optimization of processes of surface preparation and growth conditions allows to obtain MCT MBE on Si (310) without antiphase domains. Optimization of the growth process and the absence of antiphase boundaries allowed to reduce the density of morphological V-defects to $\sim 1000$ cm$^{-2}$. A technology
for the device quality undoped p-type MCT was developed. It was demonstrated that HgCdTe/CdTe/ZnTe/Si(310) could be used to create reliable, resistant to thermal cycling FPAs for the spectral ranges 3-5 and 8-12 μm.

We demonstrated the growth of single and multiple HgTe quantum wells with precise control by single wavelength ellipsometry which allows us to measure the composition and thickness of each layer during the growth. High quality single and multiple (up to 30) HgTe QWs which were grown on (013) CdTe/ZnTe/GaAs substrates was confirmed by the presence of high mobility 2D electron gas. We demonstrated the application HgTe QW for detection of the polarization state of elliptically polarized radiation from the mid-infrared to the THz range. The sensitivity and linearity of the detection system developed here has been found to be sufficient to characterize the polarization of laser radiation from low-power cw-lasers to high-power laser pulses. The short relaxation time of free carriers in semiconductors at room temperature makes it possible to detect sub-nanosecond laser pulses.

5. Acknowledgments
Authors would like to acknowledge all colleagues for taking part in fabrication, measuring parameters and scientific investigation of MCT MBE and on basis of its PV FPA’s. Especially thanks to S. Ganichev, S. Danilov, D. Kvon, E. Olshnestsikiy for measuring HgTe QW and L.D.Burdina, O.I.Malyshev, D. Ikusov, L. Mironova for growing MCT HS.

6. References
[1] Kinch M A 2000 J. Electron. Mater. 29 809
[2] Schulman J N , McGill TC 1979 Appl. Phys. Lett. 34 663
[3] Reddy M, Peterson J M, Lofgreen D D , Franklin J A , Vang T, Smith E P G , Wehner J G A , Kasai I, Bangs J W and Jonson S M 2000 J. Electron.Mater. 37 9 1274.
[4] Koestner R J and Schaake H F 1988 J. Vac.Sci.Technol. A 6 4 2834
[5] Ryu Y S, Song B S, Kang T W and Kim T W 2004 J. Mater. Sci. 39 1147
[6] Carmody M, Pasko J G , Edwall D, Piquette E, Kangas M, Freeman S, Arias J, Jacobs R, Mason W, Stoltz A, Chen Y and Dhar N K 2008 Appl.Phys. Lett. 91 091101
[7] Yakushev M V, Babenko A A, Sidorov Yu G 2009 Neorganicheskiematerialy 45 1 15 (in Russian)
[8] Ganichev S D, Kiermaier J, Weber W, Danilov S N, Schuh D, Gerl Ch, Wegscheider W, Bougeard D, Abstreiter G and Prettl W 2007 Appl.Phys. Lett. 91 091101
[9] Sidorov Yu G, Dvoretsky S A, Mihaylov N N, Yakushev M V, Varavin V S, Antsiferov A P 2000 Opticheskiy zhurnal 67 1 39 (in Russian)
[10] Kern W and Puotinen D A 1970 RCA rev. 31 187
[11] Fenner D B, Biegelsen D K and Bringans R D 1989 J.Appl. Phys. 66 419
[12] Blinov V V, Dvoretsky S A and Sidorov Yu.G. 1997 Patent of Russian Federation №2071985 Priority from 11.01.1993. Registration 20.01 1997. Bulletin №2 from 20.01.97. (in Russian)
[13] Blinov V V, Goryaev E P, Dvoretsky S A et al. 1997 Claim for invention № 95102853/25, priority from 01.03.95. Positive solution from 20.08. 1997. (in Russian)
[14] Bhan R K, Dhar V, Chaudhury P K et al. 1996 Appl. Phys. Lett. 68 17 2453
[15] Buldygin A F, Vdovin A V, Studenikin S A, et al. 1996 Avtometriya 4 73 (in Russian)
[16] Voitsehovsky A V, Denisov Yu A, Kohanenko A P, et al. 1996 Avtometriya 4 51 (in Russian)
[17] Dvoretsky S., Varavin V, Mikhailov N, Sidorov Yu, ZakharayashT, V. Vasiliev V, Ovsyuk V, Chekanova G, Nikitin M, Lartsev I, Aseev A 2005 Proc. SPIE 5964 75
[18] Wang C C and Me Farlane S H 1976 Thin Solid Films 31 3 323
[19] Sidorov Yu G , Varavin V S , Dvoretsky S A et al. 1996 J. Growth of Crystals 20 35
[20] Aoki T, Chang Y, Badano G, Zhao J, Grein C, Sivananthan S and Smith 2003 J. Electron. Mater. 32 703
[21] Tashikawa M, Yamaguchi M 1990 Appl. Phys. Lett. 56 5 484
[22] Sidorov Yu G, Dvoretsky S A, Mikhailov N N and Varavin V S 2001 Infrared focal planearrays, Nauka, Novosibirsk (in Russian)
[23] Rheenen A D, Syversen H, Haakenaesen R, Steen H, Trosdahl-Iversen L and
Lorentzen T 2006 *Phys. Scr.* **T126** 101

[24] Kuleshov V F, Kuharenko Yu A, Fridrihov S A, et al. 1985 Spectroscopy and electron diffraction in the study of solid surfaces, Nauka, Moscow (in Russian)

[25] Rogalski A 2003 *Infrared Detectors* CRC Press

[26] Spesivtsev E V and Rykhlitski S V. Useful model “Ellipsometer”. Licence No 16314. Bulletin “Useful models. Industrial samples” 35 (20.12.2000) (In Russian)

[27] Svets V A, Rykhlitski S V, Spesivtsev E V, Aulchenko N A, Mikhailov N N, Dvoretsky S A, Sidorov Yu G, Smirnov RN 2004 *Thin Solid Films* **455-456** 688