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Electro-physical characteristics of MIS structures with HgTe-based single quantum wells

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Abstract. The paper presents brief research results of the admittance of metal-insulator-semiconductor (MIS) structures based on $Hg_{1-x}Cd_xTe$ grown by molecular-beam epitaxy (MBE) method including single HgCdTe/HgTe/HgCdTe quantum wells (QW) in the surface layer. The thickness of a quantum well was 5.6 nm, and the composition of barrier layers with the thickness of 35 nm was close to 0.65. Measurements were conducted in the range of temperatures from 8 to 200 K. It is shown that for structure with quantum well based on HgTe capacitance and conductance oscillations in the strong inversion are observed. Also it is assumed these oscillations are related with the recharging of quantum levels in HgTe.

1. Introduction

HgCdTe MBE method provides new opportunities to optimize the characteristics of highly sensitive infrared detectors by growing heteroepitaxial structures based on HgCdTe with a pre-defined distribution of stochiometric composition in epitaxial films. Today the most common is creation of varyband layers with increased stochiometric composition of CdTe near the borders of the epitaxial layer. It allows reducing the influence of surface recombination on the charge carrier lifetime in the bulk of the epitaxial film, as well as to reduce the series resistance and improve the threshold characteristics of photodiodes based on p-n-junctions. Investigations of characteristics of MIS structures based on HgCdTe with inhomogeneous distribution of stochiometric composition are actual because of the need in passivation of infrared optoelectronic devices based on HgCdTe (laser diodes based on heterostructures or surface-emitting lasers [1], far-infrared range photodetectors [2]).

It should be noted that studies of the characteristics of MIS structures based on HgCdTe with inhomogeneous composition distribution are still extremely rare. The influence of surface graded-gap layers on the electrical characteristics of MIS structures based on MBE HgCdTe heteroepitaxial structures is studied in [3-5]. The properties of a MIS structure based on MBE n-$Hg_{0.75}Cd_{0.25}Te$ comprising CdTe/HgTe superlattice in the surface region of the semiconductor were experimentally investigated [6]. Also the influence of the arrangement of periodic barrier layers with sharply increasing stochiometric composition on capacitive and photoelectric characteristics of HgCdTe-based MIS structures was studied [7]. In studies of p-HgCdTe, obtained by volumetric methods, it is shown that at high hole concentration ($p > 10^{17}$ cm^{-3}) quantization of density of states in the inversion layer is possible, that leads to quantum oscillations in the strong inversion of photo-electromotive force (EMF) [8], capacitance and conductance [9].There are scientific works devoted to the research of quantumsize structures by electrophysical methods using surface-barrier structures, e.g. Schottky barriers with InGaAs/GaAs quantum-wells [10], [11] or Schottky barriers with GeSi/Si quantum dots [12].

The aim of this scientific work is the investigation of electrophysical characteristics of MIS structures based on heteroepitaxial HgCdTe with a single HgCdTe/HgTe/HgCdTe quantum well by admittance methods in wide frequency (1 kHz till 2 MHz) and temperature (8 K to 300 K) ranges.

2. Experimental methods and samples

Investigated MIS structures were fabricated by molecular-beam epitaxy method on the basis of mercury cadmium telluride on the substrates of GaAs (013) in Institute of Semiconductor physics of Siberian branch of Russian Academy of Sciences (Novosibirsk, Russia). Some of the investigated structures did not include a quantum well in the surface region. A structure with a single quantum well had a CdTe composition in the $Hg_{1-x}Cd_xTe$ barrier layer of $x = 0.65$, and the quantum well thickness was 5.6 nm. Barrier layers had a thickness of 35 nm. A low-temperature double-layer SiO_2/Si_3N_4As dielectric applied over the CdTe 40 nm layer was used as the dielectric coating. Figure 1 shows the basic layout of the layers in the structure of the quantum well, and Figure 2 shows the distribution of CdTe composition in the $Hg_{1-x}Cd_xTe$ epitaxial film for this structure.

Measurements were carried out with the use of an automated admittance spectroscopy installation based on non-optical Janis cryostat and Agilent E4980A immittance meter. The measurements were conducted with the change in voltage from negative to positive values (forward sweep scan direction measurements).

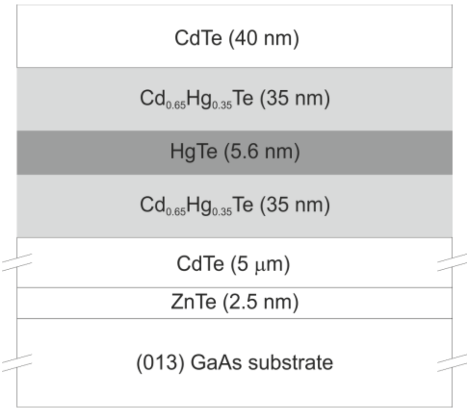

Figure 1. Scheme of the layers position in structure with single quantum well with the thickness of 5.6 nm.

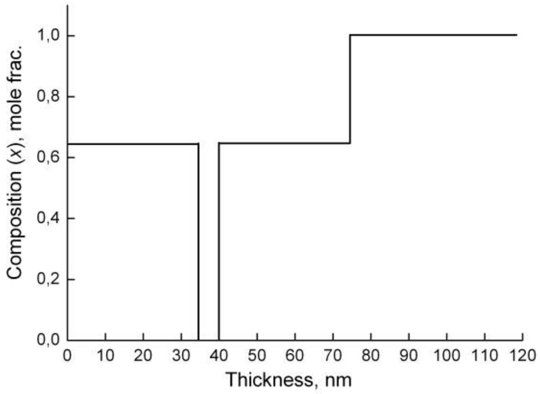

Figure 2. Composition distribution in operating layer of $Hg_{1-x}Cd_xTe$ in the structure with single quantum well with the thickness of 5.6 nm.

3. Results and discussion

Figures 3 and 4 show dependencies of capacitance and differential conductance on bias voltage for MIS structure with 5.6 nm single quantum well measured at a temperature of 7.7 K for various frequencies of alternating test signal. From Fig. 3 and 4 it may be seen that HgCdTe has a p-type conductivity, and in the area of strong inversion at the range of frequencies from 500 Hz to 100 kHz non-monotonic change in capacitance and differential conductance is observed. Capacitance maxima in this range of frequencies are observed at the same bias voltages, but for differential conductance with the change of frequency maxima can be replaced by minima for some bias voltages (Fig. 4). At 500 Hz capacitance-voltage characteristic is of low-frequency type and maxima become less pronounced than at frequencies of 5-20 kHz. At 100 kHz capacitance-voltage characteristic is close to high-frequency type and capacitance maxima also appear less clearly, than at frequencies of 5-20 kHz. The capacitance value at 100 kHz in strong inversion is close to 0.7 pF.

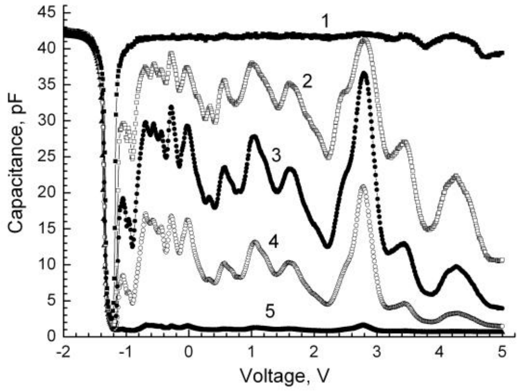

Figure 3. Capacitance-voltage characteristics of MIS structures based on HgCdTe with quantum well measured at 7.7 K under the forward direction voltage sweep at different frequencies: 1 – 500 Hz, 2 – 5 kHz, 3- 10 kHz, 4 – 20 kHz, 5 – 100 kHz.

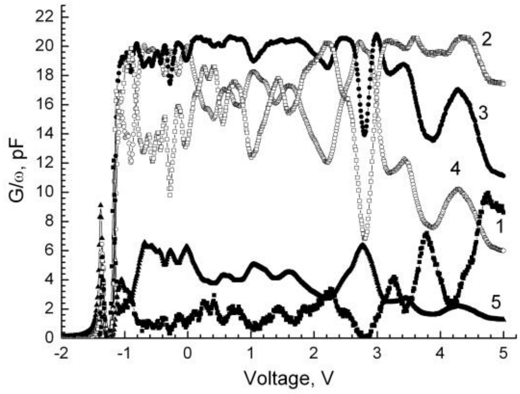

Figure 4. Dependence of differential conductance on voltage for MIS structures based on HgCdTe with quantum well measured at 7.7 K under the forward direction voltage sweep at different frequencies: 1 – 500 Hz, 2 – 5 kHz, 3- 10 kHz, 4 – 20 kHz, 5 – 100 kHz.

Figure 5 shows capacitance-voltage characteristic for a MIS structure with a quantum well measured at 10 kHz under the forward direction voltage sweep at different temperatures in the range of temperatures from 7.8 to 77 K. From fig. 5 it is seen that capacitance maxima in strong inversion are pronounced at low temperatures, and their amplitudes and position on the voltage axis change when increasing the temperature from 7.8 to 10 K. In the range of temperatures from 30 to 77 K maxima become diffused and are pronounced weakly.

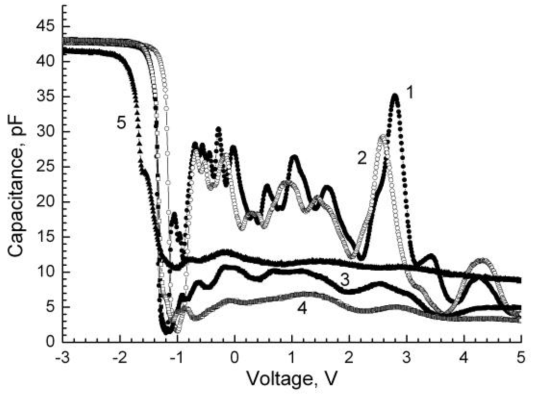

Figure 5. Capacitance-voltage characteristics of MIS structures based on HgCdTe with quantum well measured at 10 kHz under the forward direction voltage sweep at different temperatures: 1 – 7.8 K, 2 – 10 K, 3 – 30 K, 4 – 50 K, 5 – 77 K.

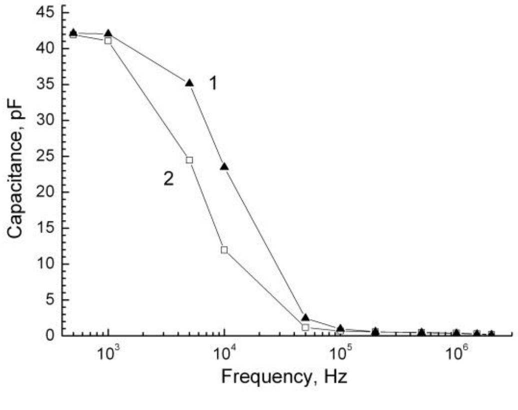

Figure 6. Frequency dependencies of capacitance of MIS structure with quantum well, measured at 8 K and different voltages: 1 – 1 V (maximum), 2 – 2 V (minimum).

Figure 6 shows capacitance dependencies on frequency for a MIS structure with a quantum well at 8 K and voltages corresponding to a maximum (1 B) and a minimum (2 B) on the capacitance-voltage characteristic. It is seen from figure 6 that a transition of capacitance-voltage characteristic from low-frequency to high-frequency type takes place with the change in frequency from 500 Hz to 100 kHz. Capacitance in the maximum at intermediate frequencies is significantly higher than in the minimum.

It must be noticed that other investigated MIS structures based on HgCdTe without quantum wells have capacitance-voltage characteristics that do not have non-monotonous changes of capacitance in strong inversion. Figure 7 shows capacitance-voltage characteristics of MIS structures based on varyband *p*-HgCdTe ($x = 0.22$) without quantum wells measured at 20 K and different frequencies of test signal. Electrophysical measurements at lower temperatures for *p*-HgCdTe ($x = 0.22$-0.36) with conversion of conductivity type after annealing are less accurate because of the sharp increase in epitaxial film's bulk resistance during cooling from 20 K to 8 K. For comparison, figure 8 shows capacitance-voltage characteristics of MIS structure based on HgCdTe with a single quantum well, measured at 30 K and various frequencies of test signal. It is seen from figures 7 and 8 that for MIS structures based on HgCdTe without quantum wells there are no non-monotonic changes of capacity in strong inversion.

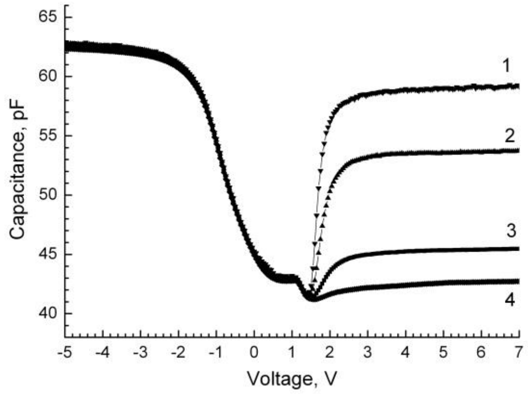

Figure 7. Capacitance-voltage characteristics of MIS structure based on varyband p-HgCdTe ($x = 0.22$) without quantum wells measured at 20 K under the forward direction voltage sweep at different frequencies: 1 – 10 Hz, 2 – 20 kHz, 3- 50 kHz, 4 – 100 kHz.

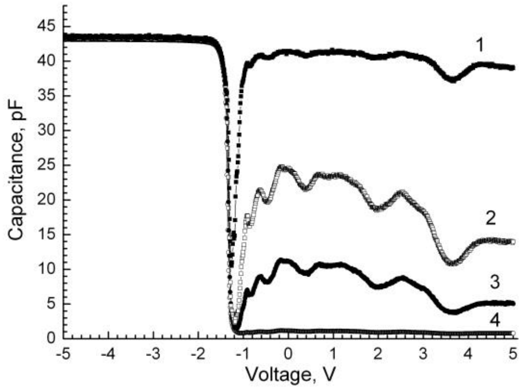

Figure 8. Capacitance-voltage characteristic of MIS structure based on HgCdTe containing quantum well measured at 30 K under the forward direction voltage sweep at different frequencies: 1 – 1 kHz, 2 – 5 kHz, 3 - 10 kHz, 4 – 50 kHz.

Thus, it is shown experimentally that capacitance maxima in strong inversion are related with the presence of a single HgTe quantum well in the structure. From the slope of capacitance-voltage characteristic in the depletion mode it is possible to define charge carrier concentration in HgCdTe, which is equal to 6.5×10^{17} m^{-3} at 7.7 K for the sample with quantum well, that is too small for the material with $x = 0.22$, but is suitable for wide band gap material with $x = 0.65$. Having known the majority charge carrier concentration it is possible to calculate capacitance value of a MIS structure in strong inversion, which was found to be 0.8 pF (experimental value is approximately 0.7 pF). The calculation of surface potential dependence on voltage for MIS structure based on HgCdTe containing quantum well is carried out.

We will briefly describe the most likely mechanism for the CVC maxima appearance in the strong inversion for the MIS structure comprising a single quantum well. Surface potential (as well as the potential in the field of quantum well) for p-HgCdTe depends on the bias voltage in the strong inversion because of the effects of degeneracy and conduction band nonparabolicity. When the Fermi level in the field of quantum well approaches to the level of quantization, quantization level recharges following a change of the AC test bias voltage. Capacity of dimensional quantization level in the quantum well contributes to the full capacity of the structure and appears at intermediate frequencies in the strong inversion. When a capacitance-voltage characteristic has a low-frequency view capacitance of the MIS structure in the strong inversion tends to the dielectric capacitance and maxima associated with dimensional quantization levels do not appear. When a capacitance-voltage characteristic has a high-frequency view the carrier concentration in the inversion layer does not have enough time to follow the test signal and contribution of the quantization levels capacitance at full capacity decreases because the quantum well is located at a distance of 35 nm from the interface. Because the charge carriers thermal energy increases with the temperature increasing dimensional quantization effects are mild.

Energies of dimensional quantization levels in a quantum well can be approximately defined by analogy with [8]. To do this, it is necessary to define the flat-band voltage in MIS structure comprising QW in terms of flat-band capacitance value and to obtain surface potentials corresponding to maxima of capacity in the strong inversion. Then it is necessary to build the potential spatial distribution in the HgCdTe surface layer and to find the potential under the given bias voltage in the quantum well. Knowing the position of the Fermi level in the flat-band mode, position of dimensional quantization levels can be find relative to the allowed energy bands in HgCdTe barriers. Crucial issue when using this method is to use the correct mathematical expressions for the main parameters of HgCdTe at low temperatures (i.e. densities of states, intrinsic concentration etc.), the proper construction of the ideal CV characteristics at low temperatures, as well as the correct numerical calculation of energy-band diagrams in the surface HgCdTe layer with taking into account the effects of degeneracy and nonparabolicity of the conduction band.

Thus the flat-band capacitance value is 33.56 pF in our case. Hence the flat-band voltage is -1.36 V. Band-gap energy of barrier layer is 0.838 eV. Fermi level location is ($E_v + 0.010$ eV) or ($E_c - 0.828$ eV). Then two first maxima of capacitance for quantum well MIS structure under the direct sweep bias voltage correspond to energies ($E_c - 0.520$ eV) and ($E_c - 0.210$ eV). Here E_c is the energy of conduction band edge of the barrier layer near the border with well.

Another way for estimation of dimensional quantization energies levels is the using of theoretical model described by us earlier in [13]. This model based on self-consistent solution of Poisson and Shrödinger equations for heterostructure comprising QW with taking into account real parameters of MBE-grown CdHgTe solid solution such as electron affinity and concentrations of ionized acceptors and donors. Calculation of dimensional quantization levels for structure under consideration at 7.7 K gives values ($E_c - 0.597$ eV) for first level of electrons E_{c1}, ($E_c - 0.347$ eV) for second level of electrons E_{c2}, ($E_c - 0.486$ eV) for first level of heavy holes E_{h1}, ($E_c - 0.517$ eV) for second level of heavy holes E_{h2}. Then two first maxima of capacitance observed on the CVC in the experiment may be associated with the presence of dimensional quantization levels. It was confirmed by estimation. But the accuracy of used calculation methods does not allow give more precise results and does not allow interpret each observed peak.

4. Conclusions

Thus the admittance of MIS structures based on MBE HgCdTe with a single 5.6 nm quantum well located in the surface layer of semiconductor was experimentally investigated. It is shown that the presence of a single quantum well thickness of 5.6 nm can lead to the appearance of capacitance-voltage and conductance-voltage characteristics peaks in the strong-inversion mode.

Capacitance maxima in the strong inversion mode are observed in an intermediate case between the low frequency and high frequency capacitance-voltage characteristics (5-50 kHz for a sample with a single quantum well). The capacitance maxima in strong inversion mode are particularly pronounced at low temperatures (8-10 K), although they are weakly apparent up to 77 K. Maxima in capacitance and conductance in strong inversion mode are not observed for samples without quantum wells. The dependences of the surface potential on voltage at various approximations are built. It is shown that considering the effects of degeneracy and non-parabolicity of the conduction band, the surface potential at strong inversion depends on the bias voltage. It is assumed that the dimensional quantization levels recharge capacitance in the quantum well contributes to the overall capacitance of the structure and appears in the capacitance-voltage characteristics in the strong inversion. An approximate method for determining the energy levels of quantum wells with the use of data obtained from the capacitance-voltage characteristics measurements is proposed.

5. Acknowledgements

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