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Determination of the donor impurity concentration in thin *i*-InGaAs layers

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This paper describes a technique that makes it possible, by analyzing the capacitance-voltage characteristics of metal–insulator–semiconductor or metal–semiconductor structures, to determine the concentration of the background donor impurity in undoped i-$In_{0.53}Ga_{0.47}As$ layers with a thickness less than the width of the space charge region in the near-surface region of the semiconductor in strong inversion mode.

Keywords: InGaAs, MIS structure, capacitance-voltage characteristic, dopant, space charge region.

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Undoped (intrinsic) layers of the i-$In_{0.53}Ga_{0.47}As$ ternary compound are used in various types and designs of discrete photodiodes, as well as in photodiode arrays [1–3] as an active photon absorption layer for detecting light radiation in the near-IR range ($1.1-1.7\,\mu$m). One of the main requirements for the i-InGaAs layer, which, as a rule, has n-type conductivity, is low ($\leqslant 10^{15}\,cm^{-3}$) concentration of background donor impurity (N_d) [1].

To determine and to monitor the value of N_d (N_d distribution through depth) in semiconductor films with a highly doped sublayer, the capacitive methods are mainly used: high-frequency voltage-capacitance ($C-V$) characteristics of metal–insulator–semiconductor (MIS) structures in depletion and inversion modes or Schottky barriers (metal–semiconductor contact) at reverse bias voltages are analyzed. As a rule, N_d is determined based on the value of the capacitance plateau in the strong inversion mode or at negative shifts for MIS-structures [4] or Schottky barriers [5], respectively. $C-V$-characteristics of MIS structures based on InGaAs were analyzed in papers [6–10]. However, this method does not allow one to determine the value of N_d in layers with a thickness less than the maximum thickness of the depletion layer — the width of the space charge region (SCR), in the strong inversion mode. This is due to the fact that the capacitance value in this case is mainly determined by the thickness of the completely depleted semiconductor layer and does not depend on N_d in it.

This paper describes the method and features of N_d determination in i-$In_{0.53}Ga_{0.47}As$ layers with a thickness less than the SCR width based on the analysis of $C-V$-characteristics of MIS structures in conjunction with theoretical calculations.

The experiments used heteroepitaxial structures i-$In_{0.53}Ga_{0.47}As$ (500 nm)/n^+-$Ga_{0.53}Al_{0.47}As$ (300 nm) grown on epi-ready semi-insulating InP (001) substrates by molecular beam epitaxy. After the layers were grown, and the plates were treated in a mixture of $HCl{:}H_2O = 1{:}10$ for 60 s, layers of SiO_2 75 nm thick were synthesized at a temperature of 195°C to remove residual oxides from sample surfaces. Round contacts with an area of $2 \cdot 10^{-3}\,cm^2$ were fabricated by deposition of Ti (20 nm)/Au (200 nm) metal layers through a mask. The ohmic contact to n^+-layer was formed by soldering In after appropriate photolithographic operations and etching of SiO_2 and i-$In_{0.53}Ga_{0.47}As$ layers at the edge of the sample. The $C-V$-characteristicsof the MIS structures were measured using Keysight B1500A impedance analyzer and a thermostated probe station in the dark.

Fig. 1 shows the temperature dependences of the $C-V$-characteristics measured at alternating signal frequency of 1 MHz. In the temperature range 270–330 K the $C-V$-curves are stretched along the stress axis due to the Fermi level fixing on interface states with a density $D_{it} > 10^{13}\,eV^{-1}\cdot cm^{-2}$ and closer to the middle of the forbidden band [9,10]. In this connection, the strong

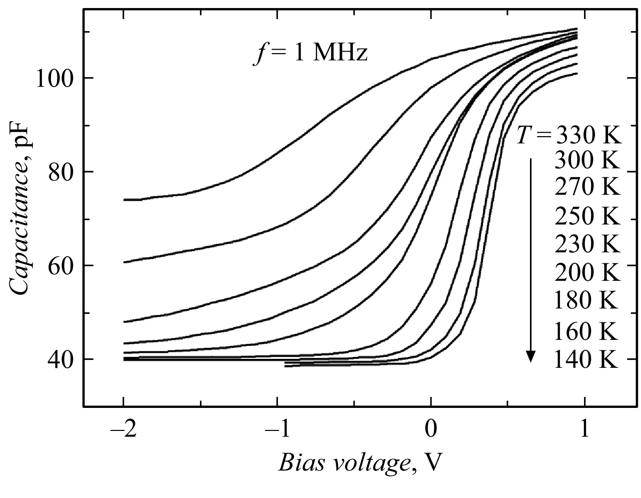

Figure 1. Temperature dependencies of $C-V$-characteristics of MIS-structures $Au/Ti/SiO_2/i$-$In_{0.53}Ga_{0.47}As$, registered at alternating signal frequency 1 MHz.

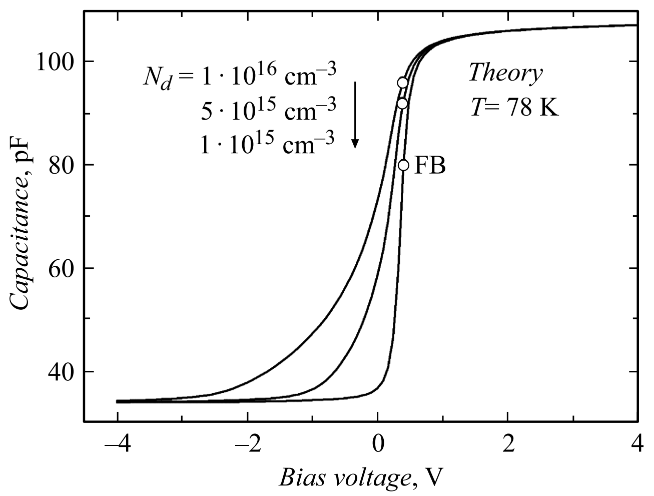

Figure 2. Theoretical $C-V$-characteristics of the MIS structure based on $In_{0.53}Ga_{0.47}As$ with $N_d = 1 \cdot 10^{15}$, $5 \cdot 10^{15}$ and $1 \cdot 10^{16}\,cm^{-3}$ at temperature of 78 K. The dots mark the capacitance of the flat bands (FB).

inversion mode is not achieved, and the concentration of the residual dopant cannot be determined. As the temperature drops below 200 K, the interface states gradually freeze out [11], which leads to the disconnection of the Fermi level and the a plateau appearance on the $C-V$-curves at negative offset voltages. Note that the capacitance decreasing in the enrichment mode (at positive offsets ~ 1 V) is mainly due to the decreasing of the relative permittivity of the SiO_2 oxide with temperature decreasing. At temperatures below 140 K the form of the $C-V$-curves does not change significantly.

Fig. 2 shows the theoretical $C-V$-curves of MIS structures of Au/Ti/SiO_2/n-$In_{0.53}Ga_{0.47}As$ at temperature of 78 K and various concentrations N_d (in the range $10^{15}-10^{16}\,cm^{-3}$), uniformly distributed through the depth of the $In_{0.53}Ga_{0.47}As$ layer. The theoretical maximum SCR width at liquid nitrogen temperature (77 K) is about 2.5 and 0.7 μm for donor impurity concentrations 10^{15} and 10^{16} cm^{-3}, respectively, which is greater than the i-$In_{0.53}Ga_{0.47}As$ layer thickness equal to 0.5 μm. Thus, the capacitance on the plateau at negative offsets is determined by the thickness of the i-$In_{0.53}Ga_{0.47}As$ layer and changes insignificantly with N_d change (at $N_d = 10^{16}\,cm^{-3}$ $C_{min} = 34$ pF, for $N_d = 10^{15}\,cm^{-3}$ $C_{min} = 33.72$ pF), which is clearly seen from Fig. 2.

The method for calculating theoretical $C-V$-curves under the assumption that there are no interface states is described in detail in [12]. The Fermi–Dirac statistics were used in the calculations, the nonparabolicity of the dispersion law and the quantization of the electron energy in the space charge region were taken into account. The $In_{0.53}Ga_{0.47}As$ parameters used in the calculations are presented in [13]. The thickness and permittivity of the SiO_2 layer in the calculations were assumed to be 75 nm and 4.8 (at 78 K), respectively.

Thus, for MIS structures with the thickness of the n-$In_{0.53}Ga_{0.47}As$ layer less than the SCR width in the near-surface region of the semiconductor, it is not possible to determine the donor concentration from measurements of the MIS structure capacitance in inversion, since the effect of N_d on the plateau at negative offsets is negligible and comparable to the accuracy of capacitance measurements.

However, as can be seen from Fig. 2, the steepness of the transition on the $C-V$-curves from the enrichment mode (positive offset voltages) to the inversion mode (negative offset voltages) strongly depends on the value of N_d. Note that in this case there is no effect of interface states on the capacitance, since the theoretical curves were calculated assuming their absence.

Fig. 3 shows the experimental frequency dependences of $C-V$-characteristics of Au/Ti/SiO_2/i-$In_{0.53}Ga_{0.47}As$ MIS structures measured at temperature of 78 K. Four characteristic regions can be distinguished on the experimental $C-V$-curves. The first region corresponds to positive offset voltages, where the capacitance decreases with frequency increasing of the alternating signal, which is mainly due to the influence of boundary traps at the SiO_2/i-$In_{0.53}Ga_{0.47}As$ interface [14] and partly with the resistance of the ohmic contact and n^+-layer.

The second region is associated with a sharp capacitance decreasing at offset voltages from -0.1 to -0.3 V (near the capacitance of flat bands), has almost no noticeable frequency dispersion, due to low $D_{it} < 10^{11}\,eV^{-1} \cdot cm^{-2}$ (78 K) near the bottom of the conduction band [9,10]. This region is extremely important for determining the donor impurity concentration with good accuracy. The coincidence of the slope of the theoretical $C-V$-curves (Fig. 3, curves *1, 2*) with the experimental ones in this region is achieved at the values $N_d = (1.2-1.4) \cdot 10^{15}\,cm^{-3}$. The

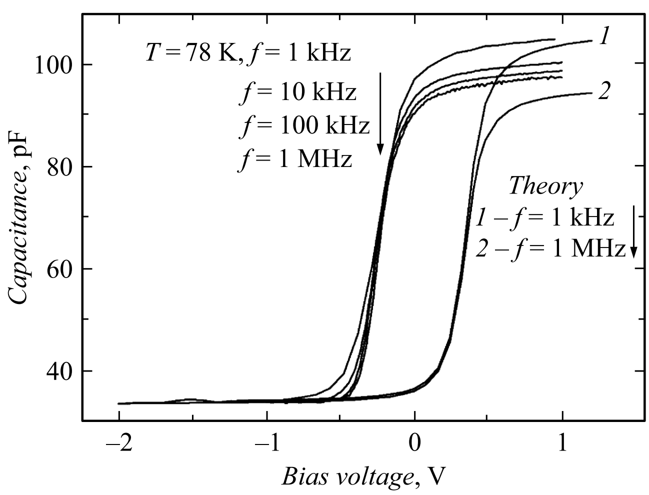

Figure 3. On the left — experimental frequency dependences of $C-V$-characteristics of Au/Ti/SiO_2/i-InGaAs MIS structures. On the right —theoretical $C-V$-characteristics at an alternating signal frequency of 1 kHz without taking into account the series resistance (*1*) and at alternating signal frequency of 1 MHz taking into account the series resistance 500 Ω (*2*).

capacitance drop in the enrichment mode with frequency increasing was compensated in the calculations by adding a series resistance. The shift of the experimental $C-V$-curve relative to the theoretical one along the stress axis by ~ 0.6 V is due to the effect of the charge built into SiO_2.

In the third region, in the range of offset voltages from -0.3 to -0.8 V, a well-defined frequency dispersion of the capacitance is observed, it is associated with the influence of interface states near the middle of the forbidden band [6–10]. The density of interface states determined from the analysis of the slope of the conditionally high-frequency experimental $C-V$-curve and the theoretical high-frequency $C-V$-curve (Fig. 3, curve *2*) in Terman method is $(4.5-5)\cdot 10^{11}\,\mathrm{eV^{-1}\cdot cm^{-2}}$ (78 K). This area is limitedly suitable for determining the donor impurity concentration. Sufficiently good agreement between the slope and the slope of the theoretical curves (Fig. 3, curves *1*, *2*) is observed only for the high-frequency (1 MHz) experimental curve.

The fourth region (plateau at negative voltages up to -2 V), as noted earlier, is determined mainly by the thickness of the $i(n)$-$In_{0.53}Ga_{0.47}As$ layer.

Thus, in paper we analyzed the temperature (78−330 K) and frequency (1 kHz−1 MHz) dependences of $C-V$-characteristics of MIS structures Au/Ti /SiO_2/i-InGaAs/n^+-InGaAs. It is shown that when the thickness of the InGaAs layers is less than the thickness of the space charge region, the donor impurity concentration in the active layer can be determined in the regions of a steep drop in capacitance (depletion and weak inversion mode), the slope of which substantially depends on the dopant concentration. At the same time, a necessary condition for this method application is the absence of a significant contribution to the capacitance of the component associated with the recharging of interface states, which can be achieved 1) by increasing the frequency of the alternating signal, 2) by passivating the interface and reducing D_{it} in the upper half of the forbidden band up to $\leqslant 10^{12}\,\mathrm{eV^{-1}\cdot cm^{-2}}$ (300 K) or 3) by decreasing the temperature of the $C-V$-measurements (freezing out the interface states).

Conflict of interest

The authors declare that they have no conflict of interest.

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