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HIGH MOBILITY 2D ELECTRON GAS IN CdTe/CdMgTe HETEROSTRUCTURES

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We report on iodine doping of molecular beam epitaxy (MBE)-grown Cd(Mn)Te quasi-bulk films and modulation-doped CdTe/$Cd_{1-y}Mg_yTe$ two-dimensional (2D) single quantum well structures. Modulation doping with iodine of CdTe/$Cd_{1-y}Mg_yTe$ structures resulted in fabrication of a 2D electron gas with mobility exceeding 10^5 $cm^2/(V\ s)$. This is the highest mobility reported in wide-gap II–VI materials.

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Since the introduction of the modulation doping concept mobilities of two-dimensional electron gases (2DEGs) in III–V quantum structures have increased by a factor of 1000, from 10^4 to 10^7 $cm^2/(V\ s)$ [1]. The improvement has been achieved by a careful design of spacer layers which move the ionized donors away from the electron gas sheet. In recent years one can observe an increased interest in transport properties of 2DEG in II–VI-based structures, especially those containing magnetic ions [2, 3]. The interest arises from the fact that such structures offer a unique opportunity for studying interaction of 2DEG with localized magnetic spins. Therefore, there is a current need for improving the mobility of 2DEG in II–VI structures. In the case of modulation doped II–VI structures the highest mobility reported so far was 4×10^4 $cm^2/(V\ s)$ [4].

In this paper we report on growth and characterization of high quality CdTe/$Cd_{1-y}Mg_yTe$ quantum well structures, exhibiting mobilities exceeding 10^5 $cm^2/(Vs)$. In order to master the use of iodine as a dopant source, we started from studying the iodine doping efficiency in thick (typically 400 nm), quasi-bulk CdTe and $Cd_{1-x}Mn_xTe$ films. Then, we used modulation doping with iodine to fabricate high-mobility 2DEG confined in a CdTe well between $Cd_{1-y}Mg_yTe$ barriers.

All our samples were grown by molecular beam epitaxy (MBE) at temperature of about 250°C using elemental sources of Cd (7N), Te (7N), Mn (5N) and a compound source of ZnI_2 (5N) for donor doping. The doped structures and/or layers were grown on hybrid substrates, i.e., on semi-insulating (100) GaAs substrates covered by 10 Å of ZnTe and, subsequently, followed by a 3–4 μm thick buffer of undoped CdTe. The magnetotransport characterization was carried out on Hall bar samples using ac technique at temperatures 1.3–4.2 K in magnetic fields up to 8.4 T. Ohmic contacts were formed by annealing indium dots in air at 180°C for 10–20 s. A Hall bar was defined by scratching the surface of the sample with a steel needle.

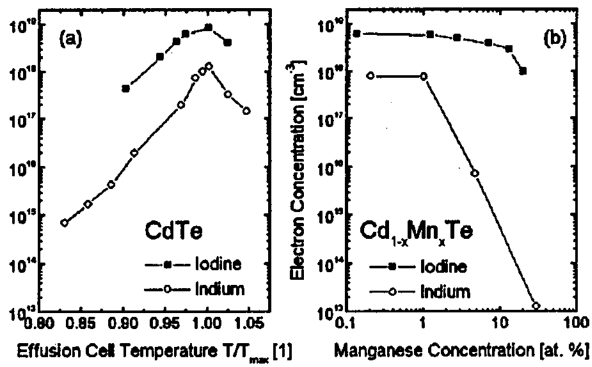

Fig. 1. Room temperature electron concentration in MBE-grown iodine- and indium--doped (a) CdTe and (b) $Cd_{1-x}Mn_xTe$ layers determined from the Hall measurements.

In Fig. 1 we compare the effectiveness of iodine doping with our best results obtained for indium doping [5]. Both, the indium and iodine doped layers were grown at similar conditions. Figure 1a shows the electron concentration in CdTe layers as a function of the reduced effusion cell temperature ($T_{\max}$ stands for In or ZnI_2-cell temperature at which electron concentrations reach their maxima). It is clearly visible that replacing indium with iodine results in much higher electron concentrations in CdTe layers. In good agreement with the previous results involving the halogen doping [6], we are able to get reproducible doping up to the level of 8×10^{18} cm^{-3}. The electron concentration in $Cd_{1-x}Mn_xTe$ epilayers as a function of manganese content is shown in Fig. 1b. Notice that in contrast to indium-doped samples, where electron concentration quickly decreases with an increasing manganese content, iodine doping of $Cd_{1-x}Mn_xTe$ enables us to keep a high doping level in samples rich in manganese [6]. Taking into account that the Mott concentration in this material is equal to about 1×10^{17} cm^{-3}, one can expect metallic conductivity in samples with Mn molar fraction up to $x = 0.3$. Thus, using iodine dopants opens perspectives for studying a very interesting issue of transport properties of a system exhibiting in a spin-glass phase.

The main emphasis of our investigation was put on 2DEG in CdTe/$Cd_{1-y}Mg_yTe$ structures. The details of design of the structures are shown in the inset of Fig. 2. The samples consist of a single quantum well (100 Å, CdTe) embedded in $Cd_{1-y}Mg_yTe$. The magnesium composition of the $Cd_{1-y}Mg_yTe$ barriers, $y = 13.5\%$, was determined from photoluminescence measurements. The quantum well was separated from the iodine doped $Cd_{1-y}Mg_yTe$ layer by an undoped 100 Å thick spacer. The modulation doping was obtained by doping a 100 Å thick layer of the barrier material. The electron sheet concentrations in different samples

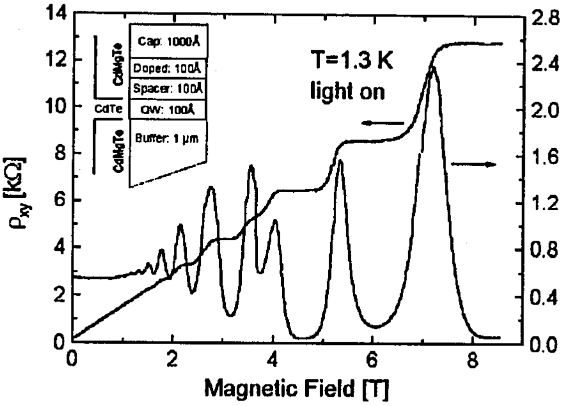

Fig. 2. Longitudinal (ρ_{xx}) and transverse (ρ_{xy}) magnetoresistance of a modulation doped CdTe/$Cd_{0.87}Mg_{0.13}Te$ single quantum well sample. The detailed design of the structure is shown in the inset.

were adjusted by changing the temperature of the iodine-cell, i.e., by changing the doping level in the doped layer. The maximum doping corresponded to the concentration of about 10^{18} cm^{-3}. In order to keep the Fermi level close to the edge of the conduction band and to avoid problems with the Ohmic contacts, in initial samples we introduced additional doped layers into the structures. In particular, we doped the 0.1 μm thick cap layer to the concentration of 10^{16} cm^{-3}. Unfortunately, such procedure resulted in formation of a parallel conductance channel bypassing the 2D conductance. The structures fabricated later, which we discuss below, did not contain any additional doped layer except the thin 100 Å doped layer. In such a case, however, the samples did not conduct in the dark at low temperatures. Therefore all measurements reported here were done under continuous illumination with a red LED.

Figure 2 shows the longitudinal (ρ_{xx}) and transverse (ρ_{xy}) magnetoresistance for a representative CdTe/$Cd_{1-y}Mg_yTe$ sample. The formation of 2DEG is clearly evidenced by quantum oscillations in ρ_{xx} and plateaux in ρ_{xy}. In one of our samples having the highest mobility of 1.3×10^5 cm^2/(V s), the Shubnikov–de Hass (SdH) oscillations start at fields as low as 0.4 T. The mobility of 2DEG in the sample shown in Fig. 2 was 7×10^4 cm^2/(V s). Assuming a circular Fermi surface, a 2D carrier concentration of 4.8×10^{11} cm^{-2} can be extracted from the SdH period, in very good agreement with the value determined from low-field Hall measurements. On the Hall effect curve (ρ_{xy}) one can recognize plateaux at filling factors $2 \le \nu \le 10$. The ultra quantum limit ($\nu = 1$) is expected at magnetic fields of 16–18 T. For $\nu \le 6$ at $T = 1.3$ K, the values of the quantized Hall resistance are in very good agreement with theoretical predictions, $1/\rho_{xy} = \nu e^2/h$. An important indication of a high quality of the sample is the clearly resolved plateau at filling factors 5 and 3. Plateaux corresponding to odd filling factors can appear only when the Landau levels become spin-split. In the case shown in Fig. 2 the spin splitting appears at fields as low as 3.5 T. At fields, where the plateaux appear in ρ_{xy}, the

ρ_{xx} signal drops nearly to zero, which is an indication that there are no important bypasses to the two-dimensional conductance.

In summary, we have reported on the growth and characterization of iodine doped CdTe-based quasi-3D epilayers and 2D quantum well structures. The 2DEG present in the structures contributes to a variety of quantum effects observed in magnetotransport measurements.

Acknowledgments

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