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Charge transfer in $Hg_{1-x}Cd_xTe$-CdTe heterostructures

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We present far-infrared magnetoabsorption experiments performed at 1.6 K in $Hg_{1-x}Cd_xTe$-CdTe heterojunctions. The results show that a two-dimensional electron gas is formed in the $Hg_{1-x}Cd_xTe$ layer at the $Hg_{1-x}Cd_xTe$-CdTe interface. The electron effective mass of the two populated subbands is obtained and compared to previous theoretical calculations. We believe that the electron transfer across the interface corresponds to a new mechanism involving deep traps in the CdTe layers.

It is now well-known that a two-dimensional electron gas occurs in modulation-doped semiconductor heterojunctions. This was first evidenced in GaAs-$Al_xGa_{1-x}As$ (Ref. 1) and $In_xGa_{1-x}As$-InP (Ref. 2) heterojunctions which have been extensively investigated and are currently used to study the integer[3] [GaAs-$Al_xGa_{1-x}As$ (Ref. 4) and $In_xGa_{1-x}As$-InP (Ref. 5)] and fractional[6] (GaAs-$Al_xGa_{1-x}As$) quantum Hall effects.

We wish to report here magneto-optical experiments at low temperatures performed on a two-dimensional electron gas in $Hg_{1-x}Cd_xCdTe$ heterojunctions grown by molecular-beam epitaxy (MBE). Because of the large energy-gap mismatch in such heterojunctions, the charge transfer corresponds, at least partly, to a new mechanism involving deep traps in the CdTe layer. We obtain also the electron effective mass of the two populated subbands occurring in the interface quantum well. Another interesting aspect of the investigated system is that, due to short growth times, there is little interdiffusion at the interfaces. The interfaces are better defined than in the $Hg_{1-x}Cd_xTe$ metal-oxide-semiconductor (MOS) structures which have been used until now to study[7] two-dimensional electron gases in II-VI compounds.

The samples (S1,S2) used here were grown[8] by MBE on GaAs substrates with the following growth sequence: for sample S1, a (100) CdTe buffer layer with thickness $d_1=2.02$ μm, a $Hg_{0.8}Cd_{0.2}Te$ layer with thickness $d_2=1.02$ μm, and a CdTe cap layer with thickness $d_3=300$ Å; for sample S2, a (100) CdTe buffer layer ($d_1=2.06$ μm), a HgTe sandwich layer with thickness $d_{sw}=100$ Å, a $Hg_{0.8}Cd_{0.2}Te$ layer ($d_2=0.89$ μm), and a CdTe cap layer ($d_3=300$ Å). The far-infrared magnetoabsorption experiments reported here were done at 1.6 K using as an infrared source a molecular laser pumped by a CO_2 laser. The transmission signal, observed at fixed photon energies, was detected by a carbon bolometer. The magnetic field B was provided by a superconducting coil and could be varied continuously up to 10 T.

Typical transmission spectra obtained at different infrared wavelengths are given in Figs. 1(a) and 2(a) for samples S1 and S2, respectively, for $\theta=0$, where θ is the angle between the direction of the magnetic field and the normal to the layer plane. Several transmission minima (i.e., absorption maxima), which are labeled A, B, C, can be clearly seen. As shown in Figs. 1(b) and 2(b), the magnetic field position of the B and C minima in both samples depends on θ, and varies roughly as $(\cos\theta)^{-1}$, indicating[9] that we are dealing with two-dimensional systems. However, the A minimum [Figs. 2(a) and 2(b)] is practically independent of θ. Figures 3(a) and 3(b) give as a function of B for samples S1 and S2, respectively, the infrared photon energy, E, corresponding to the transmission minima detected for $\theta=0$ [Figs. 1(a) and 2(a)]. From these fan charts, one can reasonably consider that the observed optical transitions extrapolate to an energy $E\sim 0$ at $B=0$. Therefore, taking into account the n-type nature of the investigated structures, as obtained from Hall experiments, these transitions are attributed to electron cyclotron-resonance transitions. The A minimum in Fig. 2(a) corresponds to bulk cyclotron resonance occurring in the $Hg_{0.8}Cd_{0.2}Te$ layer, because it is independent of θ and yields an electron effective mass m^* equal to 0.0055 m_0 at $B\sim 1$ T as obtained[10] previously in such bulk alloys. Note that the weak feature appearing in Fig. 1(b) at $B\sim 0.5$ T for $\theta=45°$ may correspond to bulk cyclotron resonance in the $Hg_{1-x}Cd_xTe$ layer , indicating that N_D-N_A is very small in sample S1. The B and C minima in Figs. 1(a) and 2(a) are interpreted as two-dimensional electron cyclotron-resonance transitions, due to the observed angular dependence. Quantum-Hall-effect measurements at 4.2 K yield a two-dimensional electron density, n_s, of a few times 10^{11} cm^{-2} for both samples, and a simple analysis of the width of these cyclotron lines yields an electron mobility $\mu\sim 5\times 10^4$ $cm^2V^{-1}sec^{-1}$ for both samples.

Thus, it is quite reasonable to consider that a two-dimensional electron gas occurs in these heterojunctions. We now seek to establish that (1) the charge transfer occurs at least in part from the wide-gap CdTe deep traps to the narrow-gap $Hg_{1-x}Cd_xTe$ layers, and (2) the ob-

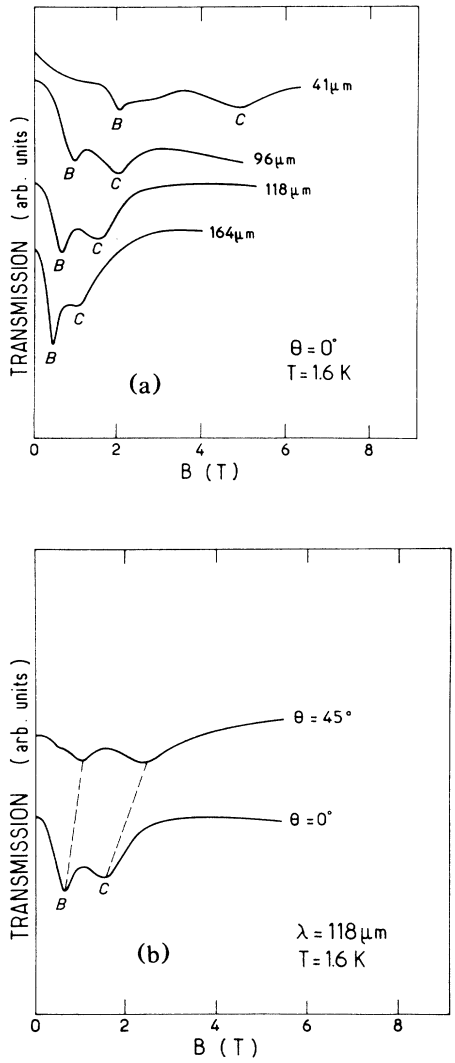

FIG. 1. (a) Typical transmission spectra as a function of the magnetic field , B, obtained for different infrared wavelengths in sample S1 at 1.6 K for $\theta=0°$, where θ is the angle between the normal to the plane of the layers and the direction of B. (b) Transmission spectra vs B obtained in sample S1 for an infrared wavelength $\lambda=118$ μm for two values of θ ($\theta=0°$ and 45°).

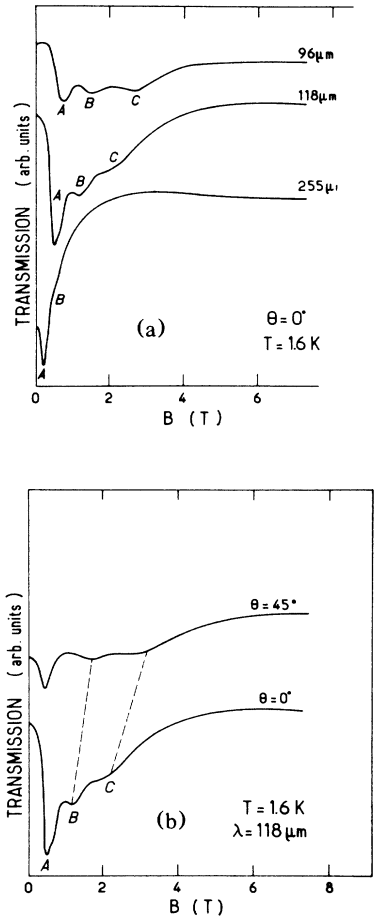

FIG. 2. (a) Typical transmission spectra obtained at 1.6 K in sample S2 for $\theta=0°$. (b) Transmission spectra obtained in sample S2 for $\lambda=118$ μm and for $\theta=0°$ and 45°.

served two-dimensional electron gas occurs at the heterojunction interface and not at the surface of the samples.

Figure 4(a) gives schematically the variation of the Γ_6 conduction- and Γ_8 valence-band edges in sample S1 in the z direction (perpendicular to the plane of the layers), taking into account electron transfer from the CdTe to the $Hg_{0.8}Cd_{0.2}Te$ layer. The band gaps of CdTe (Ref. 11) and $Hg_{0.8}Cd_{0.2}Te$ (Ref.10) are 1.6 eV and 60 meV, respectively. The valence-band offset, Λ, between these two materials is not known, but it should be roughly similar to the HgTe-CdTe offset. Unfortunately, the offset in HgTe-CdTe heterostructures is not yet firmly established, since reported values range [12-14] from 40 to 350 meV. In any case, it is substantially smaller than 0.8 eV, half the band gap of CdTe. In addition, the CdTe layer is semi-insulating and the Fermi level E_F is approximately located at the CdTe midgap, as shown[14] by x-ray photoemission measurements and transport measurements on CdTe epilayers grown under similar MBE conditions. This leads to the situation shown in Fig 4(a) and, as a result, we believe that the two-dimensional electron gas is at least partly due to electron transfer from CdTe midgap deep levels to the HgCdTe layer, even if bulk HgCdTe electrons contribute to the two-dimensional layer.

Turning to the second point enumerated above, the data shown in Fig. 3(a) imply that two electron subbands, with energies E_1 and E_2, are populated. The corresponding electron effective masses are $m_1=0.016m_0$ and $m_2=0.007m_0$ for $B\sim1$ T. The value of m_1 is comparable to that obtained[15] recently ($\sim0.015m_0$) in an inversion layer occurring in a (p-type) $Hg_{0.8}Cd_{0.2}Te$ MOS structure with a comparable electron density. Detailed agreement is not expected because the shape of the quantum well in the MOS structure is necessarily different from that in

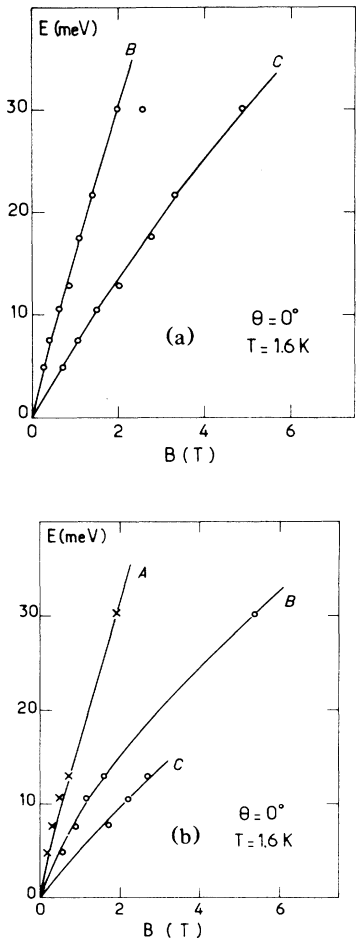

FIG. 3. (a) Position of the transmission minima for sample S1 as a function of far-infrared photon energy, E, and magnetic field, B (open circles). The middle datum at $E=30$ meV corresponds to the unidentified weak structure visible in Fig. 1(a). (b) Same data for sample S2 (crosses denote the bulk cyclotron resonance line). The solid lines are only guides to the eye.

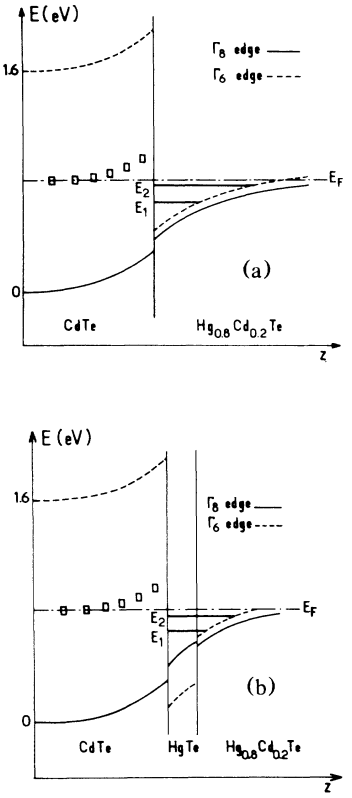

FIG. 4. Schematic variation of the conduction and valence bands in the z direction for (a) sample S1 and (b) sample S2.

sample S1, where one is dealing with an accumulation layer.

Figure 4(b) gives schematically the variation[10,12] of the Γ_8 and Γ_6 band edges in sample S2. The situation here is somewhat more complicated because of the inclusion of the HgTe sandwich layer. In HgTe, a zero-gap semiconductor, the Γ_8 band edge corresponds to degenerate conduction and heavy-hole bands, and the Γ_6 band edge to a light-hole band. However, the same reasoning as in the case of S1 leads to the scheme presented in Fig. 4(b) with again two populated electron subbands [see Fig.3 (b)]. From the results shown in Fig. 3(b), one obtains the corresponding electron effective masses of $m_1=0.023m_0$ and $m_2=0.013m_0$ at $B\sim 1$ T. In this sample, the two-dimensional electron gas is partially located in both the HgTe and $Hg_{0.8}Cd_{0.2}Te$ layers, which is a new situation in semiconductor heterojunctions. As a consequence of the HgTe conduction-band mass[10] ($\sim 0.03m_0$), m_1 and m_2 are larger in S2 than in S1. This is consistent with the two-dimensional electron gas being located at the heterojunction interface in these samples. Finally, the experimental results are unaffected by chemical etching (using bromine methanol) of the entire CdTe cap layer and up to one half of the $Hg_{0.8}Cd_{0.2}Te$ epilayer. Thus, we believe that the observed two-dimensional electron gas is located at the CdTe-$Hg_{0.8}Cd_{0.2}Te$ interface.

Unfortunately, it is not possible to make a significant comparison between the results described here and those previously reported. To the best of our knowledge, except in the case of Ref. 15,where n_s was a few times 10^{11} cm^{-2}, all experiments[16-18] have been done in accumulation or inversion layers of MOS structures with substantially larger values of n_s ($\gtrsim 10^{12}$ cm^{-2}). Similarly, reported theoretical results[19] correspond to large electron density.

However, unpublished calculations[20] on lower n_s yield two occupied subbands with $m_1=0.015m_0$ and $m_2=0.010m_0$ for $n_s\sim 2\times 10^{11}$ cm^{-2} in the case of MOS $Hg_{0.8}Cd_{0.2}Te$ structures with $N_A-N_D=10^{14}$ cm^{-3}. These values are consistent with the results obtained in sample S1. In any case, we believe that precise calculations will be complicated by the resonance between the interface wave function and the bulk $Hg_{0.8}Cd_{0.2}Te$ valence band.[7] In the case of sample S2, further complication results from the presence of the HgTe sandwich layer.

In summary, we have demonstrated that a two-dimensional electron gas can occur in $Hg_{1-x}Cd_xTe$-CdTe heterojunctions. In the structures investigated here, the electron transfer involves deep centers in the gap of the CdTe layer, corresponding to a new charge-transfer mechanism. In sample S2, the two-dimensional electron gas extends over the HgTe sandwich layer and into the adjacent $Hg_{0.8}Cd_{0.2}Te$ layer, an unusual situation not previously met in semiconductor heterojunctions which alters the electron effective masses of the two-dimensional subbands.

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