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Polarized optical properties in type-II ZnTe/CdSe multiple quantum wells induced by interface chemical bonds

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Photoluminescence (PL) and photoconductivity (PC) spectra were studied in type-II ZnTe/CdSe multiple quantum wells. It was found that the PL spectrum exhibits a strong in-plane polarization with respect to ⟨011⟩ axis with a polarization degree up to 30%. The degree of polarization does not depend on the excitation intensity and temperature, which excludes extrinsic mechanisms related to the observed in-plane anisotropy. The underlying mechanism of the observed polarization dependence of the optical properties was attributed to the inherent property of the orientation of chemical bonds in ZnTe/CdSe heterostructures with no common atom. In addition, the PC spectra also display a strong polarization dependence. Unlike the PL spectra, the PC response continuously covers a wide range of wavelengths arising from interface imperfections. We therefore point out that polarized PL and PC spectroscopies provide a unique way to probe the effects of the orientation of interface chemical bonds on semiconductor heterostructures.

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Anisotropic properties inherently exist in many crystalline solids.[1] Even though they may make it difficult to understand the physical properties of a solid, many interesting phenomena arise from the effects of anisotropy. To have a heterostructure, we need to deposit two different materials together. It therefore breaks the chemical bonds symmetry and creates new anisotropic properties. Semiconductor heterostructures, in an *AB/CD*-type combination, whose two constituents do not share a common atom, are excellent candidates to search for anisotropic effects. Indeed, the quantum structures without a common atom have nonequivalent normal and inverted interfaces, which can cause in-plane anisotropy not found in a quantum structure with equivalent interface.[2,3] It is known that semiconductor heterostructures without a common anion or cation often show a type-II band alignment and large band offset in the conduction and valence bands. The indirect transition due to spatially separated electrons and holes therefore is restricted to a very narrow region containing the interface, and the emitted radiation will exhibit the anisotropic characteristic of the interface chemical bonds.[4–6] In this paper, we report the interface-induced in-plane anisotropy in an interesting semiconductor heterostructure without common atom, i.e., ZnTe/CdSe multiple quantum wells. The degree of polarization in the photoluminescence (PL) spectra as large as 30% has been observed. Through the study of the temperature and pumping intensity dependences of the polarized PL spectra we demonstrate that the observed polarization is an intrinsic property of the ZnTe/CdSe heterostructure. In addition, we discover that the photoconductivity (PC) spectra are also very sensitive to the polarization of the incident radiation. Unlike the PL spectra, the polarization of the PC spectra can be induced by interface defects, and it covers a wide range of wavelengths. We therefore point out that polarized PC measurement is a very powerful technique to probe anisotropic defects.

All the II-VI heterostructures fabricated until now have been strained-layer system, with the exception of structures involving HgTe/CdTe and the more recently studied alloy combinations ZnCdSe/ZnMnSe.[6] The discovery that zinc-blende CdSe layers can be grown by molecular beam epitaxy (MBE) (Ref. 7) prompted several groups to attempt the growth of a different lattice-matched combination, ZnTe/CdSe. This system is unique among II-VI heterostructures in that the lattice match is obtained between two binary compounds where neither the anion nor the cation are common. The lattice parameters of ZnTe and cubic CdSe are 6.099 Å (Ref. 8) and 6.077 Å,[7] respectively, leading to lattice mismatch of only 0.3%. Because of the closely matched lattice constants, one expects negligible strain at sharp interface, thus allowing high quality superlattices with ideal interfaces to be grown. This heterostructure thus provides an excellent system for the study of the physics related to interfaces.

The multiple quantum well (MQW) structures were grown by MBE on (100) semi-insulating GaAs substrate after the deposition of about 2.16 μm of a ZnTe buffer layer. The MQW's used here contain 20 periods of alternating ZnTe and CdSe layers. The sample consists of a 120-Å ZnTe barrier layer, a 90-Å CdSe well layer, and finally a 900-Å ZnTe cap layer. Details of the growth were described elsewhere.[9]

The PL spectra were recorded by a Spectra Pro 300i monochromator and an InGaAs detector. The sample was placed inside a close-cycle He cryostat. An Ar-ion laser was used as the excitation source. For the PC measurement, Ohmic contacts were formed by depositing indium drops to the four corners of the samples, and annealing the sample at 240 °C for 10 min. A tungsten lamp dispersed by triple-grating monochromator was used as the light source. A constant current was supplied to the sample by a Keithley 236 source measure unit. The conductivity signal was detected as a change in the voltage drop across the sample using a lock-in amplifier. A detailed description of the experimental setup has been given elsewhere.[10,11]

The energy-band alignment for ZnTe/CdSe quantum well is schematically shown in Fig. 1. The energy gap at 10 K of ZnTe and CdSe are 2.4 and 1.75 eV, respectively.[8,9] The valence-band offset is 0.64 eV as determined by x-ray photoelectron spectroscopy.[12] Two types of excitonic transitions

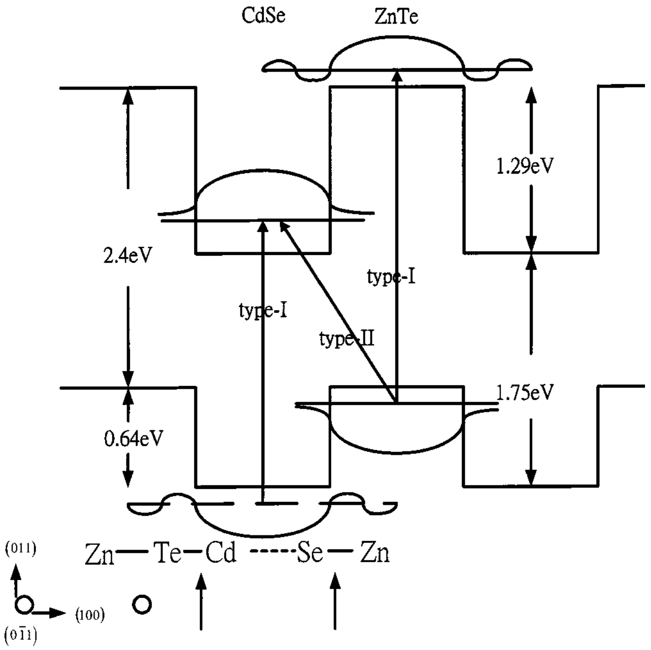

FIG. 1. Schematic diagram of the band alignment and bond sequence for ZnTe/CdSe multiple quantum wells.

are possible in such a type-II heterostructure. One takes place between electrons localized in the CdSe conduction-band wells and holes in the ZnTe wells, as shown by the arrow marked "II" in Fig. 1. The other occurs between electron (or hole) subbands confined in the wells and hole (or electron) subbands at above-barrier energies quasiconfined in the barriers. In that case both the electron and the hole states involved in the transition are localized in the same layer, as shown by the arrows marked "I" in Fig. 1. For the spatially indirect transition, it is caused by the wave-function overlap between electron and hole across interface. Because the band offset is very large (1.29 eV), the overlap region at interface is as narrow as a few monolayers. Therefore one should expect that the emitted radiation should reflect the anisotropic property of the interface chemical bonds. The interfaces in this quaternary CdSe/ZnTe heterostructure consist of Cd-Te and Zn-Se bonds; either a (011) and a $(0\bar{1}1)$ plane. It is obvious that the lower and the upper interfaces of the quantum well are not equivalent with respect to the bond directions. Their contributions to the anisotropy cannot compensate each other.[3,13] Therefore the in-plane anisotropy inherently exists in the CdSe/ZnTe MQW's studied here.

Figure 2 shows the PL spectra for the polarization of the emitted radiation along (011) and $(0\bar{1}1)$ direction. The peak at 1.03 eV corresponds to the spatially indirect transition as marked by type-II transition in Fig. 1. As we can see, the PL intensity is very sensitive to the polarization. Figure 3 shows the PL intensity versus the angle of the analyzer. Solid dots are experimental data, and the curve is fit to $\cos^2\theta$. The polarization degree defined as

$$P_l=(I_{011}-I_{0\bar{1}1})/(I_{011}+I_{0\bar{1}1}) \qquad (1)$$

can be as large as 30%. This value is too large to be explained by strain or electric-field effects.[14] In order to clarify that the observed polarized PL spectra are induced by the anisotropic nature of the interface chemical bonds, we have performed the pumping power and temperature dependences of the polarization. It is found that the degree of polarization is not sensitive to the change of pumping power in the range of 0.1–25 W/cm^2. The degree of polarization is also very stable with respect to the change of temperature from 10 to 300 K. These results can be used to rule out extrinsic mechanisms related to the in-plane anisotropy. For example, the built-in electric fields caused by unintentional doping will be screened under light irradiation. We can also exclude a significant role of localized states and nonradiative channels in the formation of the in-plane anisotropy, since they will be gradually saturated by the pumping source. We thus conclude that the polarization of the spatially indirect PL in CdSe/ZnTe is an inherent nature of the interface chemical bonds. Polarized PL measurements therefore provide a simple tool to probe interface anisotropy in quaternary heterostructures.

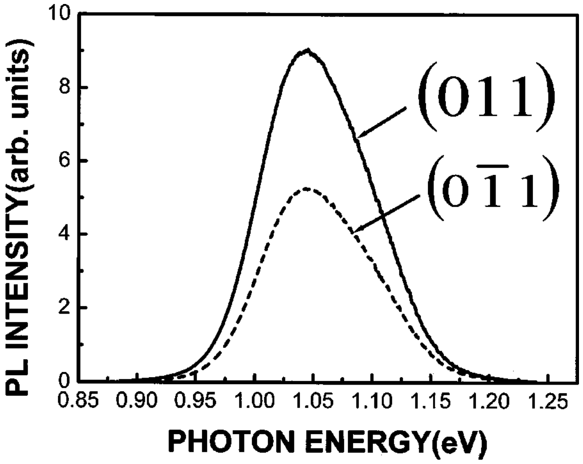

FIG. 2. Polarized photoluminescence spectra of ZnTe/CdSe MQW's under cw excitation.

Figure 4 shows the PC spectra for the incident radiation for different polarization angles. We can also see that the PC

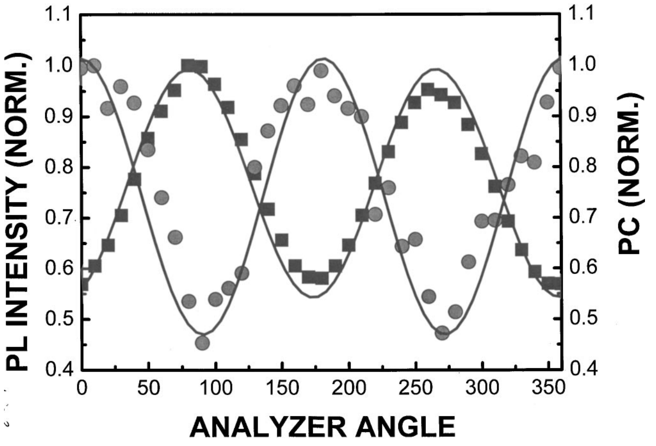

FIG. 3. Photoluminescence intensity (solid square) and polarized photoconductivity signal around 2.5 eV (solid circle) vs analyzer angle for the ZnTe/CdSe interfaces without common atom. The solid curves are $\cos^2\theta$ fit.

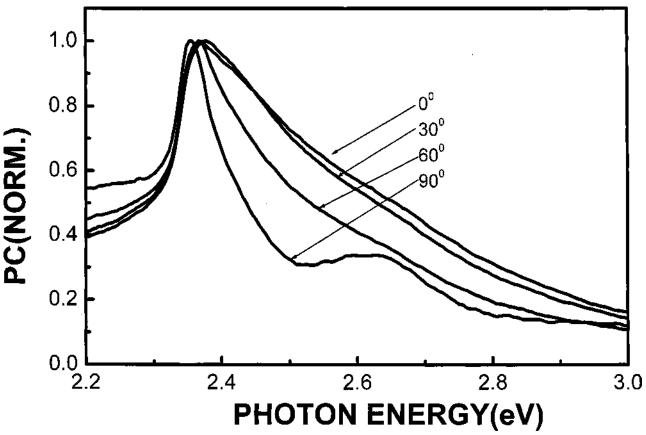

FIG. 4. Polarized photoconductivity spectra of ZnTe/CdSe MQW's.

spectra display a strong polarization dependence. The main peak at around 2.36 eV corresponds to the spatially direct transition in the ZnTe layer. It weakly depends on the polarization, which is not our main interest here. We choose the photoresponse signal at around 2.5 eV to analyze the polarization behavior. Using the same definition of the degree of the polarization defined for PL spectra, we find that the value of P can be as high as 40%. In addition, we can also see that the polarization dependence of the PC spectra covers a wide range of wavelengths as shown in Fig. 4. Figure 3 shows the polarization dependence of the PC response at around 2.5 eV. The data can also be described by the $\cos^2 \theta$ rule. The maximum and minimum signal correspond to the polarization along (011) and $(0\overline{11})$, respectively, which is similar to the behavior of the PL spectra. It indicates that the anisotropic PC response arises from the interface chemical bonds. However, the wide range response of the PC spectra as shown in Fig. 4 does not solely come from the type-I and type-II band to band transitions as marked in Fig. 1. The transition of the continuous energy states can be attributed to interface imperfections. For example, there may exist wrong bonds at the interface (e.g., Zn-Se and Cd-Te bonds in ZnTe/CdSe heterostructures), which are different from the bonds in constituent layers. These wrong bonds can be considered as a kind of localized distortion, i.e., a certain "defectlike" impurity, with respect to the host structure. Close examination of high-resolution transmission electron microscope (TEM) spectra shows the existence of reconstruction at interfaces in ZnTe/CdSe.[9,15,16] In addition, extended x-ray-absorption fine-structure (EXAFS) studies indicate the interchange of atomic layers across the interfaces.[16] Thus polarized PC spectra provide a very good opportunity to obtain the effects of microscopic interface defects in semiconductor heterostructures.

In summary, a strong polarization dependence has been observed in type-II CdSe/ZnTe QW's by photoluminescence and photoconductivity measurements. We show that the effects of anisotropy arise from the inherent nature of the interface chemical bonds in type-II heterostructures without a common atom. In addition, we point out that polarized PC measurement is a sensitive tool to probe the microscopic property of interface imperfections.

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