Wannier–Stark quantization by internal field in the HgTe/CdTe superlattice

Ikai Lo and W. C. Mitchel
WL/MLPO, Wright Laboratory, Wright–Patterson Air Force Base, Ohio 45433-6533

K. A. Harris, R. W. Yanka, L. M. Mohnkern, A. R. Reisinger, and T. H. Myers
Electronics Laboratory, General Electric Company, Syracuse, New York 13221

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The Stark ladder can be formed in a semiconductor superlattice by an applied electric field. The localization of electrons by an external electric field is known as Wannier–Stark quantization. We have performed the Shubnikov–de Haas measurements with a tilted magnetic field and the photoluminescence measurement on a HgTe/CdTe superlattice in the absence of an external electric field. From the observation of a two-dimensional electron gas and a blueshift of the photoluminescence spectrum, we conclude that the Stark ladder exists in the HgTe/CdTe superlattice and it is formed due to the Wannier–Stark quantization by the internal electrostatic field.

The motivation for growth of semiconductor superlattices (SLs) has focused on their electro-optical properties for infrared detector applications in the past decade. Recently, quantum phenomena in SLs, e.g., the Wannier–Stark quantization, have been investigated theoretically and experimentally.[1–4] The SL is a series of quantum wells (QWs) coupled by the resonant tunneling effect. Due to this resonant coupling, the original QW discrete energy levels broaden into the minibands. The electrons, delocalized in the SL miniband, occupy continuous eigenstates and show three-dimensional (3D) character. When an external electric field ϵ is applied parallel to the SL growth direction (z direction), the resonance condition is destroyed. The applied field suppresses the tunneling effect and thus isolates the different wells from each other. For a SL of period d and miniband width Δ, under a high electric field (i.e., $e\epsilon d > \Delta$, where e is the electronic charge) the SL becomes a series of isolated QWs. The electrons are confined to the isolated QWs whose eigenstates are discrete and analogous to the "Stark ladder." This localization of electrons by an external electric field is called the Wannier–Stark quantization.[5] Because the wave function in the z direction is quantized, the electron in the Stark ladder shows 2D character. As the field is increased, the band-to-band transition evolves from the miniband profile ($\epsilon=0$) to a step function at high field (due to the Stark ladder), showing a blueshifted photoluminescence (PL) spectrum. Therefore the formation of a Stark ladder can be identified by (i) the two-dimensional electron gas (2DEG) and (ii) the blueshift of PL spectrum in the SL.

Mendez *et al.* have shown the Stark ladder in a GaAs/AlGaAs SL by applying a high electric field.[2] The applied electric field tilts the SL minibands. In the high field limit, $e\epsilon d > \Delta$, the electron wave function is confined to a QW and no longer extends throughout the SL. Thus, the minibands of the SL are transformed into a series of discrete levels, the Stark ladder. However, for a SL with a small miniband width, the Wannier–Stark quantization may occur near the interface by the internal electrostatic potential $V(z)$ if the miniband bending at the interface between the substrate and the SL is strong. It is well known that the band bending in semiconductor heterojunctions is caused by the band offsets and by the attractive electrostatic potential due to the positively charged donors in the substrate. If the band bending is strong, and hence the difference of potential energy through a single QW, i.e., $V(d)-V(0)$, is larger than the miniband width Δ, the internal electrostatic field, $\epsilon = -\partial V/\partial z$, will suppress the tunneling effect and create the Stark ladder in that region. The bending of SL minibands in HgTe/CdTe SL has been studied by Hoffman *et al.*[6] They started from the simple band bending in the $CdTe/Hg_{1-x}Cd_xTe$ heterojunction. As shown in Fig. 1(a), the band bending in the $CdTe/Hg_{1-x}Cd_xTe$ heterojunction results in the accumulation of electrons at the triangle potential well. Because of the quantization of wave function in the z direction, the electrons are in discrete energy levels ($E1_{CT}$, $E2_{CT}$,...). In the case of a SL, the thick $Hg_{1-x}Cd_xTe$ layer is replaced by a HgTe/CdTe SL, see Fig. 1(b). The electrons which reside far away from the interface are in the nearly unperturbed SL levels of the minibands ($E1_{SL}$, $E2_{SL}$,...). Near the interface, as in the heterojunction, the band bending causes the energy of the minibands to be misaligned. The bending of the minibands near the interface has the same effect as applying an external electric field and results in the suppression of the tunneling effect. If the miniband width Δ is small, a Stark ladder can be easily formed at the interface between the substrate and the SL; see the first three HgTe QWs in Fig. 1(b). The internal electrostatic field in the region between the Stark ladder and the unperturbed SL is moderate and the electrons only extend through several QWs; see the intermediate region in Fig. 1(b). Because the width of the QW is very small, i.e., smaller than the de Broglie wavelength of electron, the electron wave function in the z direction is quantized. The electrons in the Stark ladder show 2D character. On the other hand, the electrons in the region far away from the interface remain nearly unperturbed and show 3D character. Therefore there are at least two types of electrons in the HgTe/CdTe SL; one is the 2DEG in the Stark ladder and the other the 3DEG in the unperturbed SL or the intermediate region. The direct evidence for the existence of the Stark ladder is the observation of a 2DEG and a blueshift of the PL spectrum. In this letter, we show the Shubnikov–de Hass (SdH) data of 2DEG as well as the blueshifted infrared PL spectrum of HgTe/CdTe SL in the absence of an external electric field. These results proved convincingly, for the first time, that a Stark ladder exists in the HgTe/CdTe SL and it is formed due to the Wannier–Stark quantization by the internal electrostatic field.

The HgTe/CdTe SL sample was grown on a (211)B CdTe substrate at 170 °C by photoassisted molecular beam epitaxy at the General Electric Company. The details of the sample preparation have been published.[7] The thicknesses of the CdTe and HgTe layers in the SL are 56 and 38 Å, respectively. The SL consists of 342 HgTe/CdTe pairs. Some optical and electrical properties of the sample have been determined by Harris *et al.*[8] In this HgTe/CdTe SL sample, two types of carriers were observed by using mobility spectrum analysis.[9] The concentration of the first carrier, having the lower mobility, decreases as the temperature decreases. It shows a strong temperature dependence. These electrons belong to the 3D miniband and move throughout the HgTe/CdTe SL. The concentration of the second carrier, having the higher mobility, is insensitive to the change of temperature. The temperature independent carrier concentration at low temperatures suggests that these higher mobility electrons may have 2D character and that they likely reside in the Stark ladder. However, the verification of 2DEG in the Stark ladder needs further evidence. The SdH effect has been used to study the properties of electron quantization.[10–12] For a system having both 2DEG and 3DEG, the suitable technique to identify the 2DEG is the orientation dependence of magnetic field in SdH measurements. When the applied magnetic field is tilted, the oscillatory magnetoresistance (R_{xx}) of 2DEG depends solely on the normal component of the magnetic field, $B_z = B\cos\theta$, where θ is the angle between the magnetic field and the z direction of the SL. Therefore, when rotating the sample from 0° to 90°, the SdH signals (R_{xx}) will change with $B\cos\theta$ and the oscillations will disappear at $\theta=90°$.[11] In the meanwhile, the oscillatory magnetoresistance of 3DEG, which depends on the external cross-section area of the Fermi surface perpendicular to the magnetic field, will not vary with $B\cos\theta$ due to the 3D Fermi surface.[12] From the SdH study in tilted magnetic fields, we are able to examine the existence of 2DEG in the HgTe/CdTe SL.

We have performed SdH measurements in the HgTe/CdTe SL for the magnetic fields up to 4.5 T. The rotating sample holder can change the orientation of the magnetic field between 0° and 130° from the z direction of the sample within 1° uncertainty. Figure 2 shows the SdH measurements at 1.4 K with the tilted magnetic fields from 0° to 90°. The zero of y axis for the small angle data was offset by one to five units, respectively, and these data were plotted on the same scale. The SdH signals are complicated due to the complexity of the narrow band gap of HgTe/CdTe SL. It is very obvious that the peaks of the oscillation shift to the higher fields as θ increases. The oscillation disappears at $\theta=90°$. If we plot these data as a function of $B\cos\theta$ (see Fig. 3), we find that the individual peak of the oscillations at different θ belong to the same Landau level. When the magnetic field is tilted, the SdH signal changes with $B\cos\theta$; the typical behavior of a 2DEG. At $\theta=90°$, no SdH oscillation is observed because the magnetic field is parallel to the 2D Fermi disk. Therefore, this oscillation is due to the 2DEG in the Stark ladder. In addition, the absence of SdH oscillation at $\theta=90°$ indicates that the mobility of the electrons in the 3D miniband is not as high as that in the 2D Stark Ladder. This property is consistent with the mobilities of these two types of electrons determined by the mobility spectrum analysis.[8] The carrier con-

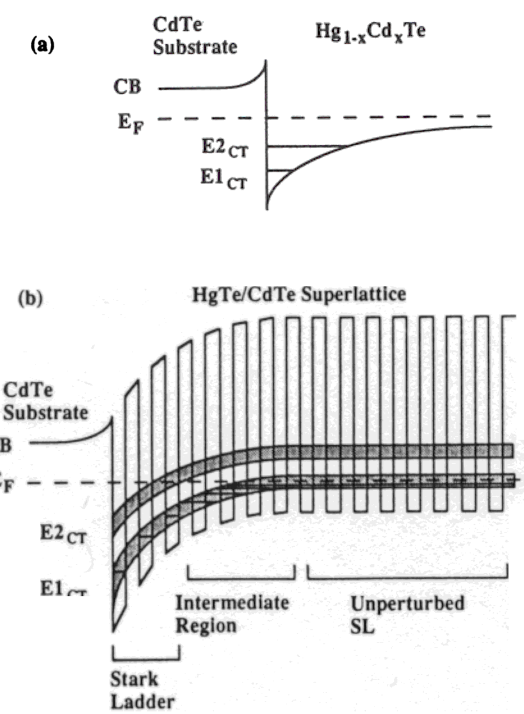

FIG. 1. The band bending in the CdTe/$Hg_{1-x}Cd_xTe$ heterojunction (a) and the miniband bending in the HgTe/CdTe SL (b). The Stark ladder is shown in the first three HgTe QWs in the SL.

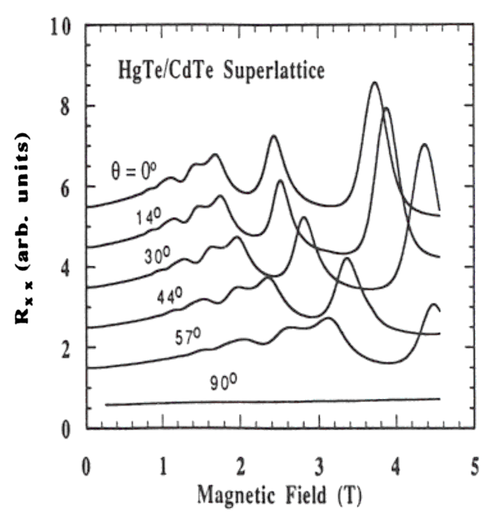

FIG. 2. The SdH measurements at different angles. R_{xx} is plotted as a function of magnetic field B.

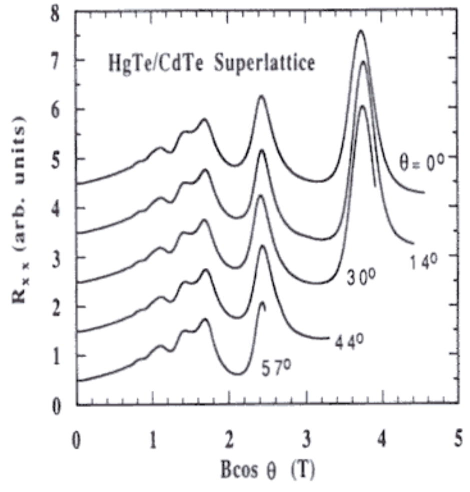

FIG. 3. The plot of R_{xx} as a function of $B \cos \theta$.

centration (n_s) of 2DEG can be calculated by the frequency of the SdH oscillation, f_{SdH}, $n_s = e f_{SdH}/\pi\hbar$, where $\hbar$ is the Planck's constant. From the Fourier analysis of the SdH data at $\theta=0°$, we obtained the carrier concentration corresponding to the primary oscillation equal to 2.95 $\times 10^{11}$ cm^{-2}. The Fermi wave vector $\mathbf{k_F}$ is equal to $(2\pi n_s)^{1/2}$. From $\mathbf{k_F}$, we obtained the Fermi wavelength, $\lambda_F = 2\pi/\mathbf{k_F} = 461.5$ Å. This wavelength is much larger than the width of HgTe QW (38 Å), thus we are sure that the electrons in the HgTe QW are 2D.

Figure 4 shows the infrared PL measurement obtained from the backside of the sample cut from the same wafer (PL excitation through the interface between the substrate and the SL). The spectrum exhibits several peaks superimposed on the higher energy side of the main peak (left-hand side in Fig. 4). The main peak energy is about 169.1 meV. Because the SL minibands in the region far away from the interface are nearly unperturbed the main peak is due to the fundamental miniband transition from the first heavy-hole band ($H1$) to the first conduction band ($E1$). In addition to the 3D miniband transition, the transitions in the Stark ladder take place in the meantime. Because of the Wannier–Stark quantization, the transitions from the Stark ladder states will show the blueshift. The peaks which shift to the higher energy in Fig. 4 are caused by the blueshift transition of the Stark ladder states in the $H1$ and $E1$ bands near the interface. The superimposition of the blueshift peaks on the main peak indicates that the 3DEG and 2DEG coexist. The blueshift of the PL peaks is consistent with the SdH results that a Stark ladder is formed in the HgTe/CdTe SL.

In conclusion, we have measured the SdH effect on the HgTe/CdTe SL in the absence of an external electric field. In the SdH measurements, we found that the peaks of the SdH oscillation shifted to the higher fields as θ increased and the oscillation disappeared at $\theta=90°$, confirming the existence of a 2DEG in the SL. The absence of SdH oscillations at $\theta=90°$ indicated that the mobility of 3DEG in the miniband is lower than that of 2DEG in the Stark ladder. A blueshift has been observed in the infrared PL spectrum as well. The PL spectrum shows that a 2DEG and 3DEG coexist in this SL. According to (i) the observation of a 2DEG and (ii) the blueshift of PL spectrum in the HgTe/CdTe SL, we conclude that the Stark ladder exists in this SL in the absence of external electric field and this ladder is formed due to the Wannier–Stark quantization by the internal electrostatic field.

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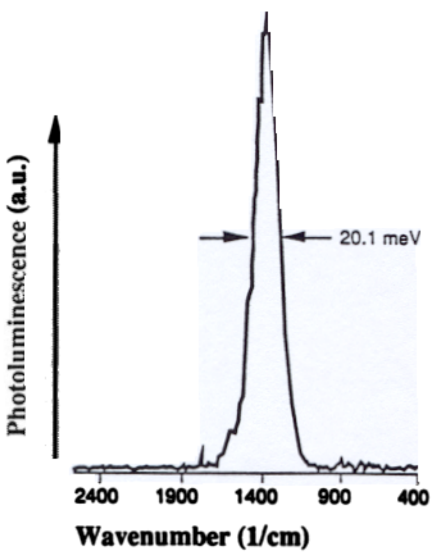

FIG. 4. The infrared PL spectrum obtained from the backside of the sample. The peaks due to the Stark ladder shift to the higher energy (left side of the main peak).

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