Above-barrier states in GaAs–AlGaAs superlattices studied by photoconductivity and photoreflectance

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We report that the quasibound states at the above-barrier region in AlGaAs–GaAs superlattices can be clearly observed at room temperature by photoconductivity as well as photoreflectance measurements. We provide concrete evidence to confirm that free-carrier confinement at barrier layer does exist. It is also found that the barrier-width dependence of the above-barrier transition energies can be described quite well by the modified Messiah’s calculation. However, the simple calculation using the constructive interference condition can only explain the transitions at lower energies, and fails with increasing transition energy. © 1999 American Institute of Physics.

I. INTRODUCTION

The confinement of electrons and holes in semiconductor quantum wells and superlattices has been investigated using a variety of experimental techniques and theoretical methods. Most studies concentrate on the energy confinement states in the well region. Recently, the existence of above-barrier quasibound states have been observed in semiconductor heterostructures. The energy states confined above the barriers of periodic potentials for the electrons and holes have been investigated by different experimental methods, such as Raman spectroscopy, photoluminescence excitation spectroscopy (PLE), absorption spectroscopy, photoreflectance spectroscopy (PR), and piezoreflectance spectroscopy (PzR). However, most previous studies were performed at very low temperature, and a clear verification of the barrier-width dependence of the transition energies has not been reported. In this article we present clear experimental evidence for the existence of above-barrier states in semiconductor superlattices at room temperature using photoconductivity (PC) and PR measurements. We show that the barrier-width dependence of the above-barrier states can be well described by the modified Messiah’s calculation.

II. EXPERIMENT

The samples were grown on GaAs substrates in a Vacuum Generators V-80H Mark II molecular beam epitaxy system. These samples consist of a 2000 Å thick GaAs buffer layer, a 2000 Å thick AlAs layer, and fifty periods of GaAs/AlGaAs superlattices. The GaAs well thickness is fixed at 50 Å, and the AlGaAs barrier thicknesses are 150, 100, and 50 Å, respectively. The AlAs layer is designed to effectively confine photoexcited carrier in the superlattices region. The characters of above-barrier states in the AlGaAs/GaAs superlattices were determined by PR and PC measurements. The experimental details of the PR measurements can be found elsewhere. In our PR measurement, a 5 mW He–Ne laser was used as the modulating source chopped at 200 Hz. The laser intensity was reduced to about 1%–10% of its initial value by using a neutral density filter. A 150 W tungsten–halogen lamp filtered by a model 270 McPherson 0.35 m monochromator provided the monochromatic light. The reflected light was detected by an EG&G type HUV-2000B silicon photodiode, and the signal was recorded from an NF Model 5610B lock-in amplifier. For the PC measurement, Ohmic contacts were formed by depositing indium drops to the four corners of the samples, and annealing the samples at 400 °C for 10 s. A tungsten lamp dispersed by an ARC Spectra Pro-275 triple-grating monochromator was used as the photoexcitation light source. The photoexcitation light was chopped by a mechanical chopper at a frequency of 200 Hz. The light beam was focused on the sample by a 10 cm focal length lens. 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 lockin amplifier.

III. RESULTS AND DISCUSSION

The PR spectrum of the superlattices with a barrier width of 150 Å at room temperature is shown in Fig. 1. The energy gap of the GaAs buffer layer locates at 1.42 eV. The energy gap of the AlGaAs barrier is at 1.71 eV which can be used to calibrate the Al content. The calibration was achieved by utilizing the expression proposed by Adachi for the energy gap of AlGaAs vs Al concentration. The feature seen in energies between the energy gaps of GaAs and AlGaAs are the transitions between the confined quantum states in the GaAs well. The spectra of the samples with barrier widths of 100 and 50 Å share similar features below 1.71 eV as shown in Fig. 1. The remaining features above 1.71 eV in the spectra arise from the transitions of the above-barrier states. We can see that the above-barrier transitions
can be clearly observed even at room temperature, indicating the strong localization of the carriers in the barrier region. In this study, we will concentrate our attention on the transitions in the barrier region.

Figure 2 shows the PR spectra for the three superlattices at room temperature. The transitions indicated by arrows are obtained from the least-squares fits of a line-shape function to the experimental data. The dotted and dashed lines represent the experimental and calculated results, respectively. Details of the line-shape function were discussed in Ref. 6. For labeling the transitions, we use the notation in which the first number indicates the conduction band state and the second the valence band state. The above-barrier transitions which involve quasiconfined states are denoted by a subscript $q$ after the number. For the sample with a barrier width of 150 Å, the three features at energies above 1.71 eV due to above-barrier transitions are attributed to $1_q^1 q$, $2_q^2 q$, and $3_q^3 q$ transitions, respectively. For the sample with a barrier width of 100 Å, we observe $1_q^1 q$ and $2_q^2 q$ transitions as shown in Fig. 1. Only the $1_q^1 q$ transition is observed for the sample with a barrier width of 50 Å. The weaker features just above the AlGaAs energy gap of the PR spectra are not due to Franz–Keldysh oscillations (FKOs), because in our PzR study on these samples we observed similar peaks at the same energy positions. According to the previous result, we should not expect to observe FKOs in PzR spectra.

Figure 3 shows the barrier-width dependence of PC spectra for the three AlGaAs/GaAs superlattices at room temperature. The features of above-barrier confined states transitions are indicated by arrows. The notation of labeling transitions are the same as that of the PR spectra. The energies of the above-barrier state transitions shown in Fig. 3 are consistent with the features observed in the PR measurement as shown in Fig. 2. The photoconductivity signals are broadening at higher energy transition. This observed broadening indicates that the high order quasibound transitions are more difficult to localize. The spectral signal at 1.77 eV in the spectrum of the sample with barrier width of 50 Å is due to the spin–orbit splitting transition of GaAs.

Let us now compare the experimental results and theoretical calculations for the energies of the above-barrier transitions. The property of localization of electrons at above barrier region can be understood from the basic quantum mechanical theory. An electron wave traveling in the barrier region experiences a reflection as it reaches the barrier–well interface. In the same way as a classical string with a different density, the standing wave will form as the constructive interference condition is satisfied. The formation of the standing wave implies the localization of the electron. The constructive interference condition is $k_b L_b = n \pi$, where $k_b$ is the wave number in the barrier region, $L_b$ is the barrier width and $n$ is an integer. The energy of the above-barrier state can be obtained by $E_b = (h k_b)^2/(2m^*)$, where $m^*$ is the effective mass of electrons or holes at the barrier region.

Figure 4 shows the energy of the above-barrier transition as a function of barrier width. The experimental results are represented by the open circles for the photoreflectance and open triangles for the photoconductivity. The conditions of localization of the wave function in the barrier region corresponding to the constructive interference condition, $k_b L_b = n \pi$, are shown as dashed curves in Fig. 4. We can clearly

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FIG. 1. The photoreflectance spectrum of GaAs–AlGaAs superlattices with a barrier width of 150 Å at 300 K. The locations of the energy gaps of GaAs and AlGaAs are indicated by arrows.

FIG. 2. The photoreflectance spectra of the above-barrier quasibound states in GaAs–AlGaAs superlattices at 300 K. The dotted lines represent experimental results, and the dashed lines are obtained by least-squares fits of a line-shape function.

FIG. 3. The photoconductivity spectra of the above-barrier quasibound states in GaAs–AlGaAs superlattices at room temperature.
see that the dashed curves can be used to describe the transitions when the confined energy is small. However, at higher transition energies the description deteriorates. Thus, the previously suggested simple constructive interference condition does not give a satisfactory interpretation of the above-barrier transition. In order to describe our experimental results, we turn to the modified Messiah’s calculation. We define the wave function $\Psi(z)$ for energies $E$, such that $V_1 < E < V_2$:

$$
\Psi(z) =
\begin{cases}
  A_0 e^{k_0 z} & z < 0 \\
  A_{bi} \cos k_{bi} z + B_{bi} \sin k_{bi} z & \text{in the } i\text{th barrier} \\
  A_{wi} \cos k_{wi} z + B_{wi} \sin k_{wi} z & \text{in the } i\text{th well} \\
  C_0 e^{-k_0 z} & z > d
\end{cases}
$$

(1)

where $V_1$, $V_2$ are the energy band offset of AlAs, Al$_{0.23}$Ga$_{0.77}$As. The $d$ is the width of superlattices, and $k_0$, $k_{bi}$, $k_{wi}$ are wave vectors of the carrier in the region of AlAs layer, the $i$th barrier, the $i$th well. The occupancy $\Omega(E)$ is defined to be the probability of a carrier being present in the superlattices region:

$$
\Omega(E) = \int_{0}^{d} |\Psi(z)|^2 \, dz,
$$

(2)

the energies at which $\Omega(E)$ have local maxima correspond to quasibound states. The effective masses and conduction-band offset described by the previous report in Ref. 7 have been used for all calculations. The eigenfunction can be found by using the matrix transformation for fifty layers. By calculating the probability of the eigenfunction, the eigenvalues of energy states are determined as solid curves in Fig. 4. Compared with the result obtained from the constructive interference condition, the transition energies given by the modified Messiah’s method have larger values. The main reason for this discrepancy may be due to the fact that in the simple constructive interference model, the effect of finite band offset has not been taken into account. As shown in Fig. 4, without any fitting parameters, the calculation of the modified Messiah’s method is in excellent agreement with the experimental results. Thus, we have provided a clear evidence for the strong localization of the carrier waves in the barrier region at room temperature.

IV. CONCLUSION

In summary, we report that the photoconductivity and photoreflectance techniques can be used to observe the above-barrier transitions in GaAs/AlGaAs superlattices at room temperature. We provide a concrete evidence for the strong localization of the carrier waves in the barrier region. We show that even though the simple standing wave condition proposed previously can give a clear physical picture, it fails to describe the energy of the above-barrier transition. It is found that the modified Messiah’s method can provide a good description.

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