



Stark-ladder transition in a $(\text{GaAs})_5/(\text{AlAs})_2$ Zener tunneling diode

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Abstract

It has been predicted that resonances between Stark-ladder states and the Zener tunneling current gives rise to oscillatory structure in the derivative of the Zener current. In order to clarify the prediction, we carried out measurements in a p-i-n diode whose intrinsic region consists of a very thin superlattice, and observed oscillatory structure in the second derivative of the current. Electreflectance (ER) measurements in the same structure were carried out to clarify the relation between the oscillatory structure in the Zener tunneling current and Stark-ladders. The results of the ER measurements are in good agreement with the calculated Zener current.

Keywords: Zener tunneling; Wannier–Stark effect; Superlattices

1. Introduction

Since Wannier predicted localization of electronic states in a high electric field, the existence of the localized states, which are called Wannier–Stark (WS) states or Stark-ladders, has been under debate. Although a number of attempts have been made to observe the localized Stark-ladder states, attempts using bulk materials have not been enough to convincingly prove the existence of the WS localization. On the other hands, Stark-ladders have been clearly observed in artificially grown superlattices with various optical measurements, such as photocurrent, photoluminescence and electreflectance (ER) [1–3]. We also have studied the behavior of Stark-ladders by measuring optical transitions in type-I and type-II GaAs/Al_xGa_{1-x}As superlattices (SLs) [4–6]. Although such optical studies have clarified the existence of the Stark-ladders, there are few reports about transport phenomena related to the Stark-ladder states.

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Recently, Di Carlo et al. [7] presented a general theory for the interband tunneling that takes into account realistic electronic structures and nonuniformity of electric fields in a device. They predicted that in a high electric field, the characteristics of the Zener tunneling current should show periodic structure due to resonances between the WS states and the Zener current.

In the previous paper we have reported observations of the WS oscillations in the Zener tunneling current and compared the results of measurements with the calculation carried out by Di Carlo et al. [8–10]. In the present work, ER measurements are carried out to compare with the observation of the WS oscillations in the Zener current.

2. Wannier–Stark oscillation in the Zener tunneling current

First, we briefly explain the mechanism of the WS oscillations in the Zener tunneling current.

When a reverse bias is applied to a highly doped p-i-n diode, electrons can tunnel from the valence band in the p-region into the conduction band in the n-region through the forbidden gap; this is the well-known Zener tunneling. In low fields, the current is dominated by the normal Zener tunneling current, resulting in I - V characteristics with a smooth dependence on voltage. Then, as the applied reverse bias is increased, the Stark-ladder states in the superlattice region overlap in energy to the Zener tunneling current. This overlap gives rise to resonance between the Stark-ladders and the Zener current. As a result, oscillatory structure in the derivative of the Zener current arises from enhancement of the Zener current due to the resonance.

The calculations have been carried out by using a realistic multi-band and multi-channel scattering theory that incorporates the periodic crystal potential and high electric field in a p-i-n structure non-perturbatively [7, 8, 11–13]. The Zener tunneling current density, J , carried by electron transfer from p- to n-region is given by

$$J(V) = \frac{-e}{(2\pi)^3 \hbar} \int dk_{\parallel} \int dE D(k_{\parallel}, E) \times [f_p(E) - f_n(E - V)], \quad (1)$$

with applied reverse voltage, $-V$. In Eq. (1), $D(k_{\parallel}, E)$ is a transmission coefficient between an in-channel state and an out-channel state, which are specified by the energy E and the two-dimensional wave vector perpendicular to the electric field direction k_{\parallel} , where e is the electronic charge, and $f_{p(n)}(E)$ is the Fermi–Dirac distribution of the wave function in the p-region (n-region).

Fig. 1 shows a comparison between the second derivative of the Zener current and the optical transition energies of the ER spectra. Fig. 1(a) shows a result of the calculation as a function of applied potential, where we find periodic oscillations in the second derivative of the Zener current, J , and the spacing between the peaks increases with increasing the applied reverse voltage. This characteristic feature is related to WS effects. For WS effects, the energy difference between each Stark-ladder is approximately expressed as $veFd$ ($v = 0, \pm 1, \pm 2, \dots$ for type-I SL; $v = \pm \frac{1}{2}, \pm \frac{3}{2}, \dots$ for type-II SL), where v is a Stark-ladder

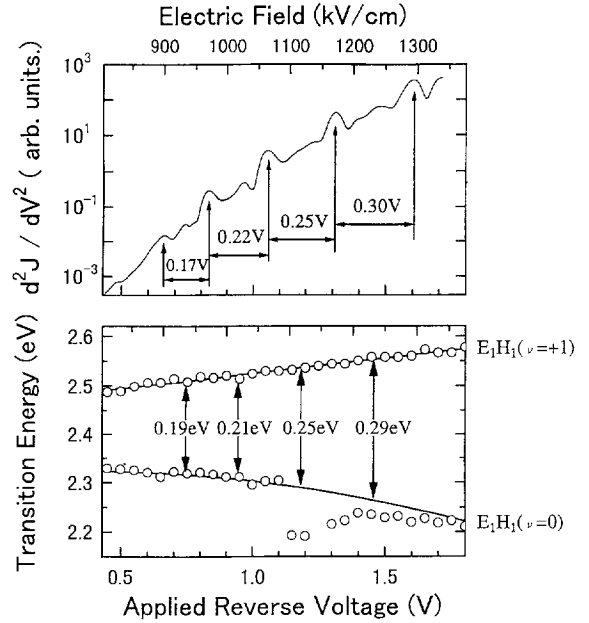


Fig. 1. Comparison between the results of the calculated J - V (a) and ER measurement (b). In Fig. 1(b) solid curves are calculated from experimental data by the least squares method.

index, F is the electric field and d is the SL period. The increase in the spacing between the oscillations found in Fig. 1(a) may be interpreted in terms of increase in the separation between the Stark-ladders with increasing the reverse bias voltage.

The arrows in Fig. 1(b) give the separation between the adjacent Stark-ladders, which are expected to agree with the spacing between the peaks in the Zener current shown in Fig. 1(a). The periods of the current density–voltage characteristics are 0.17, 0.22, 0.25 and 0.29 V. Under an applied voltage in the middle of the oscillation shown in Fig. 1(a), the differences of energy between Stark-ladder indices $v = 0$ and $v = +1$ in Fig. 1(b) are 0.19, 0.21, 0.25 and 0.29 eV.

3. Electroreflectance measurements

In order to confirm that the observed structure in the Zener current is related to the Stark-ladders, we carried out ER measurements. The intrinsic region consists of 10 periods of a undoped

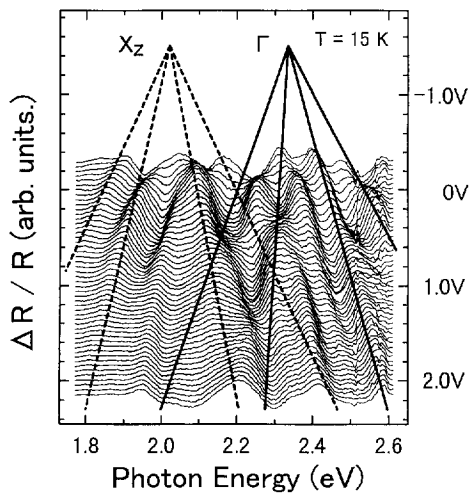


Fig. 2. Experimental results of ER. The solid and dashed lines correspond to the transitions of the Γ and X points, respectively. Transition energies are determined from the peak positions.

(GaAs)₅/(AlAs)₂ superlattice sandwiched by 30 Å nondoped GaAs spacer layers. The superlattice is placed between a p⁺- and an n⁺-GaAs layer doped with 5.0×10^{18} (Be-doped) and 5.0×10^{18} (Si-doped), respectively. The thickness of the doped layers is 5000 Å for the n-regions. The thickness of the cap layers is 500 Å so as to perform optical measurements. The sample structure used in this study is the same as the one employed in the calculation described in the previous section.

Fig. 2 shows the results of ER spectra observed at 14 K with various reverse voltages (from -0.3 to 2.15 V). The ER spectra shows several red and blue shifts in proportion to the applied voltage. As the structure used in this sample forms a type-I SL at the Γ -point in the GaAs layer and a type-II SL at the X -point in the AlAs layer, the observed spectra of the Stark-ladder transitions exhibit complicated features arising from a mixing between the Stark-ladders. In order to determine a critical transition energy of the Stark-ladder states, we calculated the transition energies using tight-binding theory. The results of experiment and calculation are shown in Fig. 3 as a function of applied voltage. The built-in potential is estimated to be 1.5 V by extrapolating the relationship between the ER spectra and the applied reverse voltage, and then the values of the

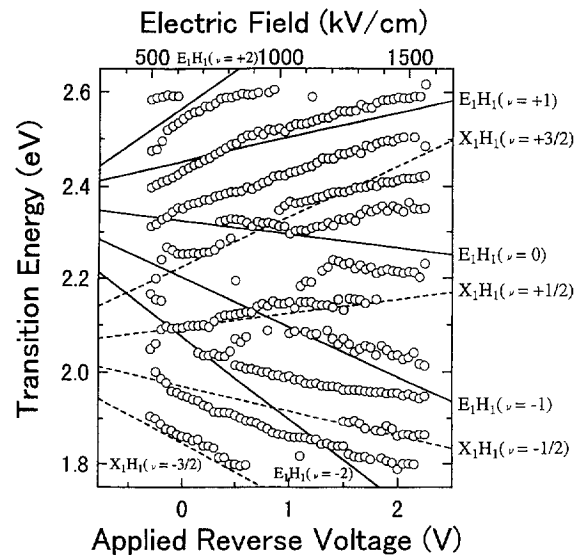


Fig. 3. The observed ER spectra and the calculated transition energies as a function of the applied reverse voltage. The open circles are determined from the ER measurements. Mixing of the ladder states is not taken into account.

electric field are obtained assuming a uniform electric field distribution in the sample. We find that the experimental data agree well with the calculated results, giving further evidence for the existence of WS oscillations in the Zener current.

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