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Wannier-Stark Localization in Superlattices

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We present experimental and theoretical evidence for Wannier-Stark (WS) oscillations in the DC electric current through reverse-biased highly doped p-i-n GaAs diodes. The intrinsic region in the diode contained seven $(GaAs)_5/(AlAs)_2$ multi-quantum wells. Carrying out these transport experiments at low temperatures, we found periodic WS oscillations in the second derivative of the Zener current, which is in qualitative agreement with theoretical predictions based on a realistic multiband and multichannel scattering theory. These findings resolve long-standing controversies about the existence of Wannier-Stark levels in the Zener tunneling current.

KEYWORDS: Zener tunneling, Wannier-Stark oscillation, p-i-n semiconductor diode, superlattice, transport

1. Introduction

Wannier-Stark (WS) localization in superlattices (SLs) has been studied extensively by observing photocurrent and optical transitions, and explained by using various theoretical methods.$^{1-5)}$ These investigations have clarified the physical mechanism of WS localization and the behavior of Stark-ladder states. We have previously studied the electric field dependence of optical transitions between WS localizations in type-I and type-II $GaAs/Al_xGa_{1-x}As$ SLs, by both electroreflectance measurements and tight-binding calculations, and were able to explain the behavior of Stark-ladders in these systems.$^{6,7)}$ All of these investigations focused on optical properties of Stark-ladder transitions. On the other hand, it has been widely doubted that localized Wannier-Stark resonances form in a regime of strong interband tunneling$^{8-10)}$ and no unambiguous observations of WS ladders in the electric DC transport have been reported up to now.$^{11)}$

A recent theory by Di Carlo *et al.* was applied to calculate the DC current in a highly reverse-biased p-i-n diode and predict a new phenomenon due to WS states.$^{12)}$ Invoking a realistic multiband and multichannel scattering approach and treating the periodic crystal potential and the nonhomogeneous high electric field in the diode on an equal footing, this theory predicts an oscillatory structure in the current-voltage characteristics (WS oscillations in Zener tunneling current, as shown in Fig. 1) and takes into consideration the interplay between Stark-ladder states and Zener tunneling. In a p-i-n diode with a voltage drop that exceeds the band gap, the external electric field accelerates the electrons in the p-region towards the n-region through the (classically forbidden) intrinsic region; this is the well-known interband or Zener tunneling from the valence into the conduction band. When the intrinsic (i) region consists of a SL, the Zener tunneling current resonates with the WS levels that are formed in the i-region. These resonances enhance the tunneling probability and give rise to WS oscillations in the current-voltage characteristics.

In the present study, we have carried out measurements of the Zener tunneling current in a $(GaAs)_5/(AlAs)_2$ SL in order to clarify the existence of the WS oscillations in a DC transport experiment.

2. Zener Tunneling Current

In the theory developed by Di Carlo *et al.*, the Zener current has been evaluated using a transfer matrix method based on a realistic spin-orbit-sp^3s^* tight-binding model.$^{13)}$ In contrast to the conventional transfer matrix method based on the effective mass approximation, this multiband approach properly accounts for the interband mixing effects (between the valence band and the conduction band) that are induced by an electric field.

When a reverse bias (−V) is applied to the sample, the Zener tunneling current carried by electron transfer from the p- to n-region is given by

$$j(V) = \frac{-e}{(2\pi)^3\hbar}\int dk_{//}\int dE\ D(k_{//},E) \times [f_{\mathrm{p}}(E) - f_{\mathrm{n}}(E-V)]\,, \qquad (1)$$

where $D(k_{//},E)$ is the tunneling coefficient for an in-channel state specified by the energy E and a two-dimensional wave vector perpendicular to the electric

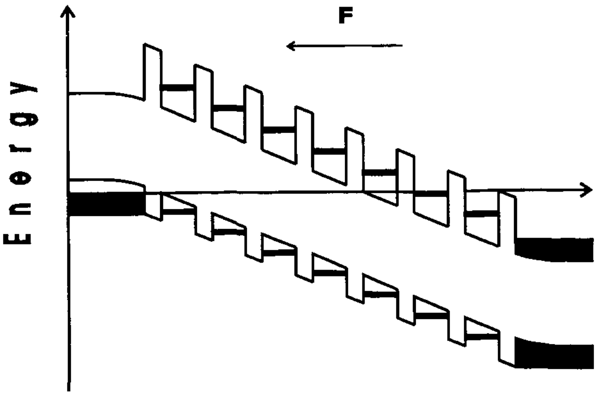

Fig. 1. Illustration of Wannier-Stark oscillation in Zener tunneling current.

field direction $k_{//}$, e is the electronic charge, and $f_{\mathrm{p(n)}}(E)$ is the Fermi-Dirac distribution function in the p-region (n-region). The tunneling coefficient is evaluated from the transfer matrix $T(k_{//},E)$ given by the product of matrices $T_j(k_{//},E)$ (j runs over the SL layers) connecting the amplitudes of the atomic orbitals in one atomic layer with the amplitudes in the neighboring layers:

$$T(k_{//},E) = S_{\mathrm{p}}^{\dagger}(k_{//},E)\prod_j T_j(k_{//},E-V_j) \times S_{\mathrm{n}}(k_{//},E-V). \qquad (2)$$

To clarify this approach, let us consider a simple example with one orbital per atom. In this case, $T_j(k_{//},E)$ is given by

$$T_j(k_{//},E-V_j) = \begin{pmatrix} 0 & 1 \\ -1 & -\dfrac{\epsilon-E-V_j}{t(k_{//})} \end{pmatrix}, \qquad (3)$$

where $S_{\mathrm{p(n)}}(k_{//},E)$ is the eigenstate in the p-region (n-region), ϵ is the orbital energy, and t the transfer integral, respectively. Obviously, the matrix T_j is more complicated in the actual multiband calculation based on the sp^3s^* basis.

As a concrete application, we have considered a p-i-n structure with highly doped p- and n-regions, and with a thin intrinsic multi-quantum-well structure consisting of 7 periods of $(\mathrm{GaAs})_5/(\mathrm{AlAs})_2$. The doping concentrations in the n- and p-regions are 5×10^{18} cm^{-3}. The sample structure is shown schematically in Fig. 2. Figure 3 shows the calculated second derivative of the Zener tunneling current of this structure. For an applied reverse bias exceeding 1.2 V, the calculations show several peaks that arise from the WS oscillations. The separation between the peaks increases with increasing applied reverse voltage due to the fact that the energy separation between neighboring WS levels becomes larger with increasing voltage.

In order to check this prediction, we have measured the current-voltage characteristics of the sample depicted in Fig. 2. The sample was processed into a mesa structure with a square shape of 150 μm × 150 μm. Ohmic contacts were provided by an evaporation deposition technique with Au and AuGe/Au at the top and the bottom, respectively. The measurements were carried out at 10 K.

Figure 4 shows the second derivative of the measured current density as a function of the applied reverse voltage. The experimental findings (solid curve) are compared with the predictions (dashed curve) already shown in Fig. 3. In the experiment, the second derivative of

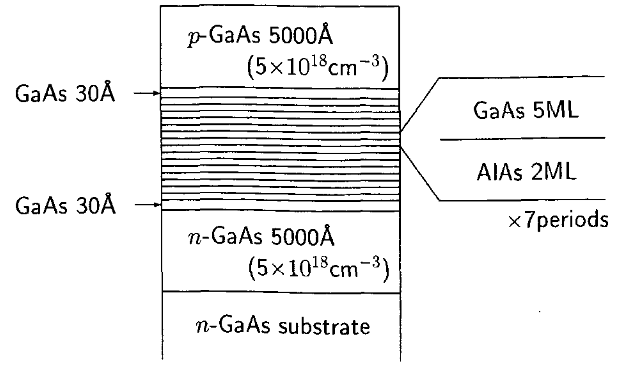

Fig. 2. Schematic sample structure used in the calculations and measurements.

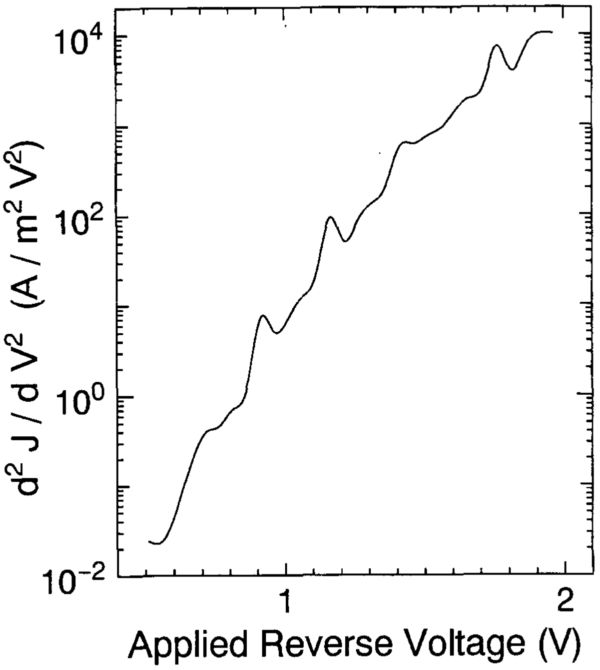

Fig. 3. Calculated second derivative of the Zener tunneling current density in a p-i-n diode containing a $(\mathrm{GaAs})_5/(\mathrm{AlAs})_2$ superlattice with reverse voltage.

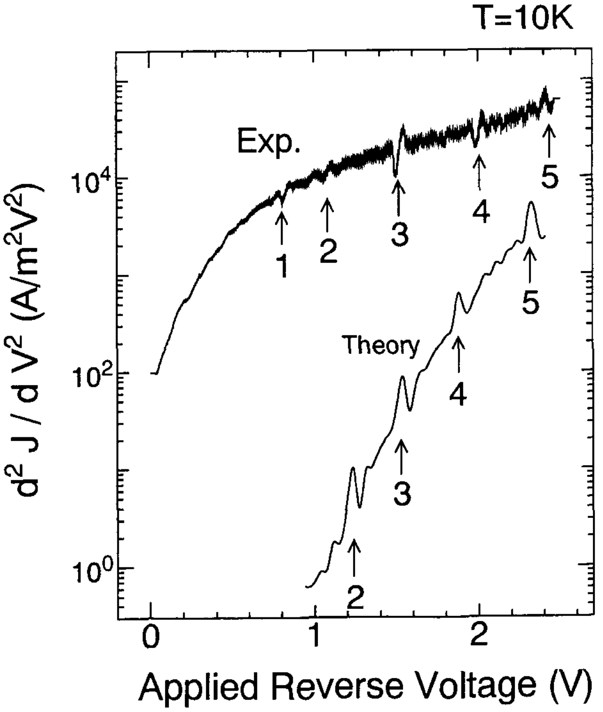

Fig. 4. Experimental result of second derivative Zener current measured at T = 10 K, where the theoretical calculations are shown for comparison. The solid curve is the experimental result and the dashed curve is the calculated result.

the current is obtained from the average of twenty measurements of the Zener current in order to increase the signal-to-noise ratio. We find a distinct periodic structure in the second derivative of the current density. The observed oscillations appear reproducibly in every sample prepared from the same wafer. Although the absolute magnitude of the measured current is significantly larger than the calculated one, the positions and the separation between the extrema are in good agreement with the calculated results. The separation of the peaks increases with increasing reverse bias both in experiment and in theory. The discrepancy between the calculated and measured absolute magnitudes of the current can be significantly reduced (i) by taking into account some intermixing of Ga and Al in the AlAs layers in the calculations, rather than assuming abrupt interfaces and (ii) by adjusting the width and area of the active tunneling region by a few percent.

The observed features clearly indicate the existence of WS oscillations in the Zener tunneling current. Therefore the present data provide, to our knowledge, the first evidence for the formation of WS ladders in the context of DC transport.

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